A Backpressure-based Algorithm for Optimal Scheduling in Freight Management Systems

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***Abstract*—In this work, we present a novel, backpressure-based algorithm for optimal scheduling in freight management (logistics) systems. Although scheduling has been extensively addressed within the logistics domain, there are various remaining open challenges regarding scalability, stability, and quality of transfer requirements. We provide an alternative approach for logistics systems, which capitalizes on the principles of backpressure scheduling, originally proposed for joint packet routing and scheduling in computer and communication networks. Our penultimate goal is to develop a broader framework addressing all the previously mentioned open challenges. We present a first, simple, functional instance of this framework through a specific algorithm addressing mainly the issues of scalability of scheduling and stability of the whole system, ensuring that the system load will not cause an explosion of the unsent backlog at any time. Additionally, we provide simulation results on its performance, demonstrating its potentials, and thus paving the way for a broader exploitation that enables optimal routing-scheduling decisions in logistics systems.**

***Index Terms*—Backpressure scheduling; Logistics; Information systems; Performance evaluation.**

I. Introduction

Freight management systems and supply chains have become a significant functionality of modern societies. Occasional failures, especially at the global level, as was the case with the 2021 Suez Canal obstruction [1], may lead to immense costs and waste of resources, along with major delivery delays. The field of Operations Research has devoted its effort to optimizing supply chains and logistics systems in general, aiming towards reducing financial costs, improving response times and increasing quality features of interest, e.g., priority handling, special packaging, etc.

Scheduling and routing of packages (of various sizes and weights) constitutes the core of logistics and supply chain management. Scheduling in general, regards the assignment of resources to the execution of tasks, where in the logistics domain the resources may constitute loading space, packet volume/weight, etc., and the tasks regard the delivery of packages, storage management, etc. Several approaches have been employed for optimal or sub-optimal scheduling in logistics systems, such as linear programming, combinatorial optimization, dynamic programming, stochastic optimal control, multi-objective optimization and network flows [2].

In this work, we introduce a novel framework for optimal scheduling-routing in logistics system, in which decisions for routing and scheduling are made via a backpressure algorithmic approach. Routing regards where to send a package at the next time instance, while scheduling regards when to send it once the next destination is determined. The proposed framework follows the general design principles set in [2] and presents a mathematical framework for its implementation. Specifically, a modified version of the backpressure algorithm for joint scheduling-routing is proposed with the goal to holistically optimize the respective decisions of a whole supply chain ecosystem, consisting of multiple source-destinations and an intermediate multihop distribution network. This will typically include either a very large freight management company, or an ecosystem of smaller and small-medium companies and individual contractors, in which case the proposed algorithm suggests in the form of a regulation authority optimal decisions. We map such logistics problem where multiple freight companies and independent contractors want to send packets from sources to destinations accounting for the time-varying availability of the transportation means as well as their limited capacities. Furthermore, we introduce a novel implementation of the backpressure approach for logistics, which ensures that in one time-step the complete set of transportation resources between a node pair is utilized, i.e., that no intermediate transportation means remains under-utilized. We present evaluation results on the behavior and performance of the specific algorithms demonstrating the feasibility of the overall framework and its potential for optimizing logistics systems management. The novelty of this work is in the proposed modified backpressure algorithm, which is designed in such a way that it could be used by a regulation authority or a coalition in a logistics ecosystem to optimize routing and transfer decisions accordingly. We present both the mathematical framework and its evaluation,

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in order to gain insights of its potential performance benefits and its eventual adoption in operational information systems.

The rest of this paper is organized as follows. Section II presents relevant works and distinguishes our contribution from them. Section III formulates the problem to be solved and sketches the proposed solution. Section IV defines the employed system model and Section V presents the proposed backpressure-based algorithm for logistics applications. Section VI provides indicative results on the performance and behavior of the proposed approach, and finally, Section VII concludes the paper and highlights directions for future work.

II. Background & Related Work

The backpressure algorithm was first proposed in [3] for multihop communications networks consisting of two jointly optimized stages, namely, a routing stage based on differential backlogs and a link scheduling stage by solving a maximum weight matching problem. Routing refers to determining a path that a packet will follow from its source to its destination, which in logistics refers to determining the whole path a package will follow, from destination to its source, including the intermediate warehouses and branch shops stored. The backpressure algorithm does not determine the whole path initially, but at every time t it determines the next node that the packet needs to be sent at, therefore optimizing routing decisions dynamically according to the current system state (congestion level). Scheduling refers to whether this packet should be sent at time t to the next (intermediate) destination or not.

The backpressure algorithm has the advantages of being throughput optimal, adaptable to time-varying network conditions and applicable without a-priori knowledge on the network traffic characteristics. Due to these advantages, it has been enhanced and adapted for diverse applications such as for traffic lights management [4], for energy management in energy harvesting networks [5] and for traffic flows with diverse characteristics such as delay requirements [6]. Despite the important advantages of the adaptability and throughput optimality of the backpressure algorithm, its deployment to other application areas including logistics can be impeded by the fact that it can lead to high delays in packet transfer due to the emergence of routing loops, the slow-start problem, as well as the last packet problem in low traffic conditions [7].

Several approaches exist to solve the delay problems of the backpressure algorithm. The authors in [7] apply the drift-plus-penalty technique to account for the lifetime of the packets and packets are discarded if they have not reached the destination within specific time limits. In [8], the authors suggest a variation of the backpressure algorithm aided by shortest-path routing and in particular, they reduce packet delays but reducing the length of the paths followed by the traffic. In our previous work in [9], we propose a weighted backpressure algorithm that scales the congestion gradients with the appropriately defined per-pair (link, destination) weights. In this way it achieves performance-awareness with respect to a given measure, such as delay, which is linked to the definition of the weights. In [10] delay improvements are achieved by using LIFO instead of FIFO queues. Priority packets are handled in [6] via storing them in different queues than the ordinary packets. Finally, [11] develops a loop-free backpressure algorithm using directed acyclic graphs.

Logistics have gained considerable interest from the beginning of the 1900s but more systematically following the World War II, where it became apparent that efficient and timely deliveries can be game-changers. Scheduling in supply chain management can take the form of: a) transfer cost minimization, b) production scheduling, and c) joint criteria optimization, e.g., cost reduction and failure minimization. In [12] the authors solve a problem where a constructor receives raw material from a producer, and delivers products to a customer, all in different location, with the goal of minimizing the cumulative production-transfer cost (including raw material and delivery costs). This is a representative of the second category and in [12] it is shown that the production cost can be combined in a uniform expression for all production schemes in the case that all processes have the same duration. An $O(n)$ algorithm is proposed as a solution. In [13] the impact of multiple scheduling stages is studied, for two-stage processes in a logistics system. A forward and a backward approach for solving the sequential stages is taken, reaching heuristic solutions in both cases. The work in [14] studies a scheduling problem in the last-mile, the final node before the end customer, of a supply chain. Assuming specific truck delivery times, the optimal routes for the last-mile are designed, assuming the last hop can be flexible. The work in [15] focuses on a single-stage scheduling problem, where tasks are delivered in batches. A branch-&-bound solution is proposed for minimizing the withhold and transfer cost.

The above approaches for scheduling in logistics systems, are more targeted and do not provide holistic solutions. Our approach aspires to fill in this gap. The two stages of the backpressure algorithm, i.e., routing and scheduling, are also required for packet transfer in logistics applications, since for each packet we should decide to which warehouse it should be transferred next and if it will be transferred by the current or a later transportation means e.g., truck, train or plane. Thus, given also its advantages and accounting for its enhancements for delay reductions, the backpressure algorithm has a strong potential for solving the packet transfer problem for freight companies and to the best of our knowledge, this has not been studied in the literature yet.

III. Problem Formulation & Proposed Solution

Freight companies have among others the following requirements when transporting packages:

- The transports should be fast, reliable and low-cost.
- The transports should be dynamically adjusted based on the time-varying remaining capacities of the transport means and of the warehouses.
- The priority packages should be expedited within specific time limits.

The backpressure algorithm is ideal for taking dynamic decisions on packet transfer and with its extensions, briefly described in Section II, can be adjusted for achieving delay and cost goals as well as for handling priority packets. Thus, in this paper, we propose for the first time a backpressure-based joint routing and scheduling algorithm for logistics applications. In particular, we use appropriate extensions of the backpressure algorithm to achieve the goals of the logistics companies as well as propose new extensions that are necessary for deploying the backpressure algorithm to handle freight companies' traffic. In particular, first, our approach groups packages into separate queues depending on whether they are characterized as emergency (i.e., high priority) or ordinary, similarly with [6]. Second, it avoids routing cycles by segregating queues according to the hop count to reach the destination of each package similarly with [8]. Third, its novel feature is that it exploits the full available link capacities at all times by filling up any remaining link capacities with packets that do not belong to the queues achieving the maximum queue differentials.

IV. System Model

Consider a logistics network described by a directed graph $G = (N, L)$ with N the set of nodes and L the set of directed links. The nodes correspond to warehouses or premises of logistics companies. A link between nodes i and j is indexed by $(i, j) \in L$. Each link (i, j) at time t has a capacity $c(i, j, t)$ expressed in m^3. The capacity varies with time depending on the availability of transport means between i and j. In particular, if $c(i, j, t) = 0$ there is no possibility of packet transfer between i and j and if $c(i, j, t) > 0$ transport means (e.g., vehicles) with aggregated capacity $c(i, j, t)$ are available between i and j. A flow represents packet traffic sent from a particular source node to a particular destination node. There can be multiple flows between the same source-destination pair with different characteristics, e.g., priority level.

In any case, we can compute the hop distance between all pairs of nodes-warehouses, e.g., by applying the Dijkstra's algorithm on G. This distance may be considered constant for the purposes of our study, since it varies rather slowly, e.g., yearly, due to the cost of adding/removing warehouses and/or carrier branches.

Each node maintains two types of queues, namely H ordinary and H emergency queues with H the maximum hop distance for all node-pairs in G. H can be trivially set to $|N| - 1$ with $|N|$ the cardinality of set N. Let $Q_i^{emg,h}(t)$ and $Q_i^h(t)$ be respectively, the emergency and ordinary queue of node i that holds all packets to be transferred in at most h-hops to their final destination. Note that with $Q_i^{emg,h}(t)$, $Q_i^h(t)$ we denote both the queue structures and the aggregated space filled by the packets currently stored in the queues in m^3.

Each node-warehouse i may introduce new packet traffic denoted as $a_i^{emg,h}(t)$ and $a_i^h(t)$ regarding the amount of emergency and ordinary traffic, correspondingly, in m^3, generated at i, at time t with hop index h.

Moreover, assume $r^{emg}(i, j, t)$ and $r(i, j, t)$ are the amounts of emergency and ordinary packets, respectively, all in m^3, which need to be transferred over link (i, j) at time t bounded by the capacity of link (i, j), i.e., under the constraint $r^{emg}(i, j, t) + r(i, j, t) \leq c(i, j, t)$.

We denote by N_i the set of one-hop neighbors of i. Also, assume $Y(t)$ a time-varying set of sets of links. A set $I \in Y(t)$ is a subset of L containing links that can sent concurrently packets, depending on the availability of the transportation means at t. $Y(t)$ is time-varying since different vehicles, trucks, ships, containers, etc., can be available at different times and each $I \in Y(t)$ corresponds to different links that can be formed based on different routes of the available transportation means, given that a link can be formed only if there is an available transportation means for the connection of the corresponding nodes. For instance, let us assume two trucks with capacities tc_1, tc_2 (in m^3). At time t, the truck 1 can move from warehouse 1 to 2 and the truck 2 from 2 to 3 or from 2 to 4. Then, $Y(t) = \{I_1 = \{(1, 2), (2, 3)\}, I_2 = \{(1, 2), (2, 4)\}\}$. The capacity of each link will be equal to the capacity of the corresponding available transportation means. In the same example, for I_1, $c(1, 2, t) = tc_1$, $c(2, 3, t) = tc_2$, $c(2, 4, t) = 0$ and for I_2, $c(1, 2, t) = tc_1$, $c(2, 3, t) = 0$, $c(2, 4, t) = tc_2$.

Finally, we assume that the system is in its steady state and that the ergodic limits of arrival processes $a_i^{emg,h}(t)$, $a_i^h(t)$, lie in the capacity region of the network.

V. Backpressure-based Algorithm for Logistics

In this section, we describe the proposed backpressure-based algorithm for logistics applications.

For each link in L we compute the optimal differential backlog, $\Delta Q^*(i, j, t)$, as follows:

If the emergency queues of node i are not empty, we will process packets from the emergency queues and packets from the ordinary queues will be transferred only if available space remains. In this case, we define:

$$\Delta Q^*(i, j, t) = \max_{h=1 \ldots H} \{\max\{Q_i^{emg,h}(t) - Q_i^{emg,h-1}(t), 0\}\}. \quad (1)$$

Otherwise, if the emergency queues of node i are empty, packets from the ordinary queues will be served. We define as:

$$\Delta Q^*(i, j, t) = \max_{h=1 \ldots H} \{\max\{Q_i^h(t) - Q_i^{h-1}(t), 0\}\}. \quad (2)$$

Let h^* be the optimal number of hops that achieves $\Delta Q^*(i, j, t)$.

Once $\Delta Q^*(i, j, t)$ is computed for all links $(i, j) \in L$, we solve a maximum weight matching problem to determine the optimal set of links that will carry packets at time t. The maximum weight matching problem can be written as:

$$\max_{\forall I \in Y(t)} \sum_{(i,j) \in I} c(i, j, t) \Delta Q^*(i, j, t). \quad (3)$$

Let us assume that I^* is the solution of the above problem. If a link is selected for packet transfer, which means it belongs to I^*, the selection of packets to be transferred on is performed as follows:

1) If the priority queues of node i are non-empty, then (i, j) will first serve packets in $Q_i^{emg,h^*}(t)$, which achieves the maximum $\Delta Q^*(i,j,t)$. If $c(i,j,t) > Q_i^{emg,h^*}(t)$, then the link can serve more packets such that the available space, e.g., of a truck does not remain partially unused. For this, the link first ranks all remaining priority queues (apart from h^*) according to the differences $Q_i^{emg,h}(t) - Q_i^{emg,h-1}(t)$. Assuming an ordering from the first to last is $h_1, h_2, ..., h_{H_{emg}-1}$, where H_{emg} is the number of emergency queues (taking into account the one served already) and if h_k ranks higher than h_l, this means that $Q_i^{emg,h_k}(t) - Q_j^{emg,h_k-1}(t) > Q_i^{emg,h_l}(t) - Q_j^{emg,h_l-1}(t)$. Then (i, j) starts serving packets from queues ranked higher, namely first with h_1, then h_2, etc., until the capacity of the link is exhausted or there is no remaining packet to be served. If node i has served all packets from the emergency queues but there is still available space in the link, it will serve packets from the ordinary queues. In this case, following a similar procedure the ordinary queues are ranked based on the difference $Q_i^h(t) - Q_j^{h-1}(t)$ with higher priority determined by higher position of the queue in the ranking. The link serves packets from ordinary queues starting with those having higher rank if available space remains.
2) If the emergency queues of node i are empty, then link (i, j) will serve packets from ordinary queues and more specifically from queue $Q_i^{h^*}(t)$ achieving maximum $\Delta Q^*(i,j,t)$. If $c(i,j,t) > Q_i^{h^*}(t)$ then the link can serve mode packets from other ordinary queues to exploit completely the available space in the link. To do so, similarly to the previous case, the link first ranks the remaining ordinary queues according to the differences $Q_i^h(t) - Q_j^{h-1}(t)$ with higher values indicating higher priority. The link will serve packets starting from queues higher in the ranking as long as there is still available space.

Then the amount of packets to be transferred in the link in m^3 for an emergency queue with index h, denoted as $r^{emg,h}(i,j,t)$ is given by:

$$r^{emg,h}(i,j,t) = \sum_{p \text{ served from } Q_i^{emg,h}(t)} l(p), \tag{4}$$

where $l(p)$ is the space occupied by packet p.

Similarly, the amount of packets to be transferred in the link in m^3 for an ordinary queue with index h, denoted as $r^h(i,j,t)$ is given by:

$$r^h(i,j,t) = \sum_{p \text{ served from } Q_i^h(t)} l(p). \tag{5}$$

The queue's occupancy update for the emergency queues takes place according to:

$$Q_i^{emg,h}(t+1) = \max\{Q_i^{emg,h}(t) - \sum_{j \in N_i} r^{emg,h}(i,j,t), 0\} + \sum_{j: i \in N_j} r^{emg,h+1}(j,i,t) + a_i^{emg,h}(t), \tag{6}$$

Similarly, the update of ordinary queues is as follows:

$$Q_i^h(t+1) = \max\{Q_i^h(t) - \sum_{(j \in N_i} r^h(i,j,t), 0\} + \sum_{j: i \in N_j} r^{h+1}(j,i,t) + a_i^h(t). \tag{7}$$

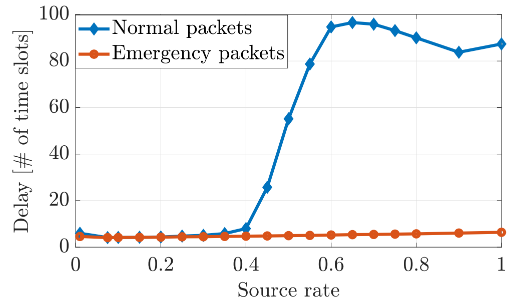
VI. Evaluation Results

In this section we evaluate the proposed algorithm based on simulations. The main goal of the evaluations is to provide some guidelines to the freight companies and in particular (i) to show how to estimate source rates that can be handled with low delays for both emergency and ordinary packets, i.e., to show how to estimate the capacity region of a logistics network and (ii) to show how to estimate a critical number of emergency flows or a critical amount of emergency traffic under which the network can guarantee delay and service rate requirements for the emergency packets. However, the presented evaluation of the scalability of the proposed algorithm is quite more demanding than in a real case scenario of an operation freight company. Essentially our evaluation setting determines a complete freight ecosystem with multiple logistics SMEs and transport contractors.

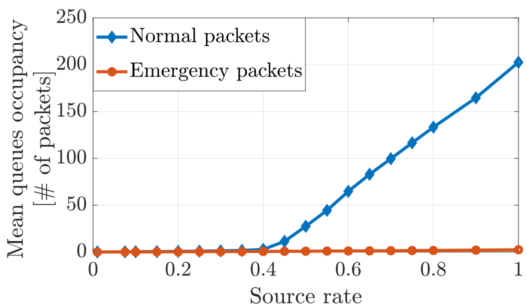
We assume the network of [Fig. 3, 16]. All nodes produce ordinary packets for sink node 1. Our experiments are for three cases with respect to the number of emergency flows as shown in Figures 1, 2 and 3. In particular, the nodes that produce emergency traffic for sink node 14 are indicated in the legend of each figure.

We study three metrics for both ordinary and emergency packets, namely, mean delay, number of served packets and mean queues occupancy. Delay is for all packets including both those already served and those currently stored in queues. The source rate in the x-axis corresponds to the probability that a source of ordinary or emergency packets produces a packet. Each source produces packets independently of the others. The capacity of all links is set to 5 for all time steps.

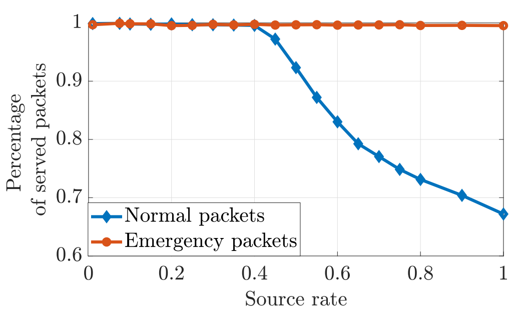
Figure 1 shows the evaluation results for light emergency traffic over the network. In Figure 1(a), the mean delay of ordinary and emergency packets is compared for different source rates. The curve of the mean delay of ordinary packets has similar shape as the one shown in Figures 9 and 10 of [6], i.e., it initially increases and then decreases for higher source rates. Figures 1(b), 1(c) compare the occupancy of the queues and the percentage of served packets over the total number of produced packets, correspondingly, between ordinary and emergency traffic. We observe that under sufficiently low emergency traffic, the emergency packets can be guaranteed almost zero end-to-end delay and 100% service rate for source rates that are common in logistics applications.



(a) Mean delay of all packets.

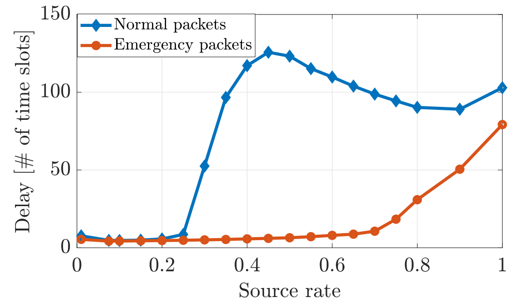


(b) Mean queues occupancy in number of packets.

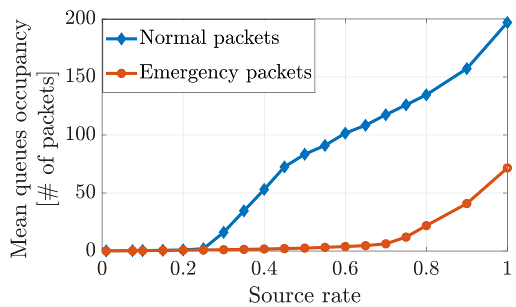


(c) Number of served packets.

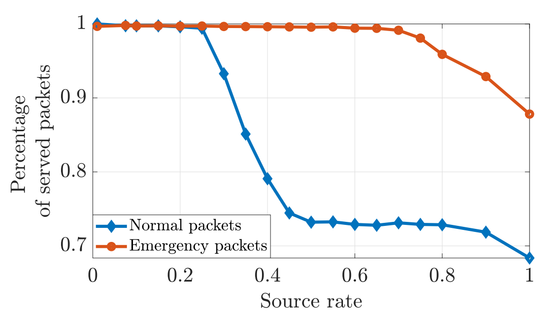
Fig. 1. Evaluation results with 5 emergency flows and 11 ordinary flows. Nodes $2, 4, 6, 8, 10$ produce emergency packets for node 14.



(a) Mean delay of all packets.



(b) Mean queues occupancy in number of packets.



(c) Number of served packets.

Fig. 2. Evaluation results with 10 emergency flows and 11 ordinary flows. Nodes $2 - 12$ produce emergency packets for node 14.

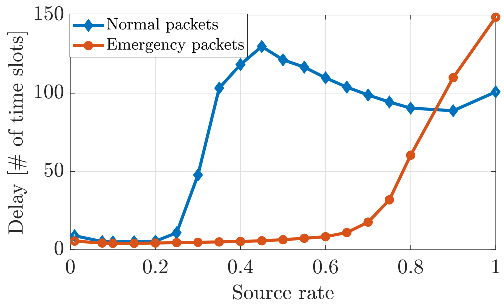
Figure 2 depicts the same metrics as Figure 1 but with increased emergency traffic. We observe that for source rates higher than 0.7, the emergency packets start having considerable delays and there exist unserved emergency packets that occupy the queues.

The number of emergency flows is further increased in Figure 3, where now there exist as many emergency flows as ordinary flows. In this case, the values of source rates for which emergency packets can be supported with 100% service rates and negligible delays should be smaller than 0.6. Importantly, we observe that for higher source rates, larger than 0.8 in value, the delay of the emergency packets becomes even larger than the one of the ordinary packets. Thus, there exist no guarantees that the emergency packets will be served faster than ordinary packets although they are still given much higher service rates than the ordinary packets.

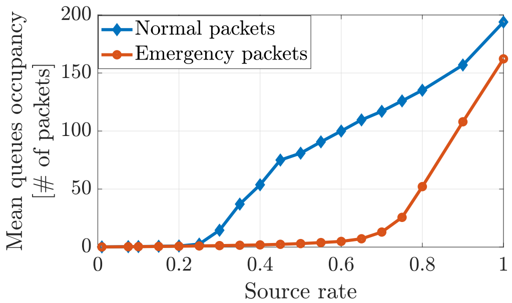
To sum up, if the number of emergency flows is sufficiently small, the emergency packets are guaranteed almost zero delays and 100% service rates. As the number of emergency flows increases, the delays of the emergency packets increase and after a critical threshold of emergency flows may become higher than those of the ordinary packets, i.e., there exist no guarantees for the emergency packets. In our test case, the critical number of emergency flows is equal to the number of ordinary flows.

VII. Conclusion

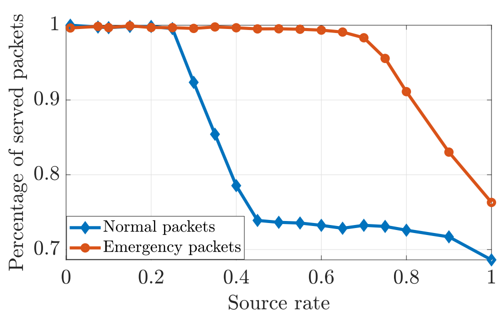
In this paper we presented a first mathematical approach for a holistic joint routing-scheduling decision-making framework for a logistics/freight management ecosystem. Based on the proposed backpressure approach, optimal, scalable and stable decisions can be made on where to send the packet next (routing) and when to send (scheduling) the packet once the next destination is determined. The approach dynamically adapts to the traffic conditions of the system, accounts for different packet priorities and exploits the full available transport capacity at every time. Through analysis and simulations, we showed that it can be successful in ensuring the scalability



(a) Mean delay of all packets.



(b) Mean queues occupancy in number of packets.



(c) Number of served packets.

Fig. 3. Evaluation results with 11 emergency flows and 11 ordinary flows. Nodes $2-13$ produce emergency packets for node 14.

and stability of the logistics ecosystem. Furthermore, there is significant room for extending the presented algorithm into a broader decision-making framework, since several additional quality-of-transfer criteria can be imposed and aim at e.g., various concurrent goals, such as cost reduction via utility functions.

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