Dynamic Cargo Routing on-the-Go: The Case of Urban Solid Waste Collection

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***Abstract*—Efficient collection of urban solid waste is a growing problem for cities and urban areas. Optimizing service routes based on actual waste bin fill level information can result in significant cost savings, reduced emissions, and improved city image. Fill level sensor installation and networking at an urban scale poses unique challenges. We describe Dynacargo, an innovative smart city application that leverages RFID technology in the waste bins and delay-tolerant networking (DTN) in roaming vehicles acting as mobile sinks. Dynacargo collects and transmits waste bin status information to the backend systems utilizing already existing network infrastructures and single-hop communications thus, reducing associated costs and time for installation, operation, and management of the necessary networks and ICT systems.**

I. Introduction

There are six major categories of waste: industrial (manufacturing); construction and demolition; mining and quarrying, agricultural and forestry; radioactive; and urban solid waste. While the formers involve only a handful of collection points (e.g., plants), predictable waste production, and long filling periods, urban solid waste involves numerous waste bins that exhibit significant filling variations and must be emptied many times per week or even per day.

A poor or inappropriate urban solid waste collection system can introduce or amplify problems affecting the urban environment, the authorities, and the citizens. Main sources of problems and debate include: time of collection; plan and frequency of collection; waste bin placement; number and capacity of waste bins; garbage truck routes; and age of the fleet. On the other hand, an optimized collection system allows reductions in traffic congestion, noise levels, emissions, and costs, while improving public image and general sense of duty for public cleanliness [1].

Urban solid waste bins are still emptied *by experience* and *a good guess approach*, although the benefits of utilizing *actual status information*, like fill level, frequency of use, and environmental conditions are evident [2], [3], [4]. Significant reductions can be achieved not only by optimizing the service routes but also when a garbage truck avoids to idle as to allow service personnel to check if a waste bin should be emptied or not. Idling and low-speed moving -even when unloaded- can account to more than 50% of a truck's emissions during a service route.

The collection of actual status information about the waste bins of a whole city or municipality requires the deployment and operation of sensors at *urban scale*: hundreds or even thousands of sparsely-distributed sensors installed in waste bins in populated areas. As an example, about 20,000 waste bins are installed throughout the city of Berlin in Germany. At this scale, network connectivity and formation problems become apparent. The communication cost for using cellular networks becomes prohibitively large; the short-range multi-hop networks can be unmanageable and unreliable; and a very large number of long-range gateways (e.g., WiFi) must be installed and operated to cover the whole area of a city.

In this paper, we present Dynacargo, an innovative system that requires minimal infrastructure costs and handles urban-scale waste bin status information collection. Short-range sensors are installed in the waste bins. Vehicles passing by the bins collect status information, acting as mobile sinks. While roaming around the city, the vehicles explore connectivity opportunities, like through WiFi hotspots, and, using delay-tolerant networking (DTN), they send the collected information to the waste collection system for further processing.

The rest of the paper is organized as follows. In Section II, we present requirements and challenges for integrating field information in an urban solid waste management system, while in Section III, we revisit existing approaches in the literature. Section IV presents the Dynacargo approach, while Section V discusses the mobile sink system design and the challenges faced. Finally, Section VI concludes our paper and presents future directions of work.

II. Requirements and Challenges

The implementation of an efficient urban solid waste[1] management system for a city is a challenging task. It requires not only the optimal use diminishing city budgets but also the increased satisfaction of the city visitors and citizens for the quality of the experience they receive.

Earlier attempts to solve the waste collection problem i.e., the garbage truck fleet routing problem, did not consider any variations in the waste bin fill levels [5]. The collection and the integration of information regarding the actual status of waste bins in the field can assist city planners into devising waste collection plans that serve both aforementioned aims.

In the next, we consider the requirements and challenges for collecting waste bin information from the field at an

[1]For the sake of simplicity, we shall use the terms "waste" and "urban solid waste" interchangeably hereon.

urban scale. The areas of attention include the integration of sensors in waste bins, the accuracy in measuring the fill level, any additional information that must be collected, and the transmission of the information to the waste management backend systems.

A. Urban Solid Waste Bins

The *waste bin identification* for inventory management is the most elementary information processed by a waste management system. Advances in RFID technology allow the use of RFID tags for fast bin identification. A patrol service can be realized by driving near the waste bin equipped with an RFID reader. The driver or a backend system can be notified of missing bins and initiate necessary investigation. It can also be used to postpone routing a garbage truck to the specific area, until a bin is installed again. This can result in significant cost savings.

The *fill level* is an indicator for emptying a bin. Once filled, the citizens cannot use it, they may be annoyed, and they may even leave their waste next to the bins. This results in emptying delays since the waste must be handpicked by service personnel while the truck idles, in a bad city image, and in possible environmental and hygiene threats. On the other hand, frequently servicing near-empty bins is not an optimal use of the available resources.

The *fill level estimation* of a solid waste bin is not an easy task. Unlike liquid or granular materials, randomly-placed solid objects of different shapes and dimensions severely hamper the estimation accuracy. Only a handful of works are published on *sensing solid waste level* or fill, mostly focused on specific waste types. Examples include paper [6]; corrugated board and cardboard [2]; recyclable materials (Tecmic Ecogest); moisture content for combustion in a furnace [7], optical sensing [8], and camera image processing for urban solid waste [9], [4], [10]. The environmental conditions around or inside the bin may affect significantly a sensor's operation. Example conditions include ambient light, humidity, moisture, and dust. This can lead to unreliable measurements and need for frequent sensor cleaning.

It may be beneficial to collect additional information regarding a waste bin, such as *loading events* (time and frequency) and *weight*. This information could be used to plan better service (reduce the time that the waste stays in the bin) and to optimize routes. Garbage trucks can compress the waste once loaded on truck and reduce its volume. Trucks are weight-saturated in contrast to waste bins that are volume-saturated. Weight limits must be obeyed for safety and truck-health reasons. On the other hand, citizens observe the waste volume in a bin, which also affects the image of the city. Thus, a good combined estimator of volume and weight can be beneficial. However, we notice that it is simpler to record service time and waste weight during the loading process of the waste in the garbage truck, rather than integrate such sensors in the bin.

Service delays can occur for a wide range of reasons. *Environment sensors* (e.g., air quality) could provide additional information on the exact conditions so as to assess the accompanying risks and received citizen complaints.

Waste bins are *manufactured of different materials*, such as plastic (PVC), metal (aluminum), or a combination of them. The variety and the specific materials must be considered in order to ensure proper operation, sensing, and communication of electronic devices. The size and shape of waste bins is not standardized thus, sensing systems may need to be adapted to a specific design and shape.

The *economic benefits* of the so-called "smart bins" are still not well-received by many decision makers. In many cases, it requires a large upfront investment to replace the existing waste bins. This cost cannot be fully justified. In response, waste bin manufactures have not introduced waste bins with intelligence integrated in their frames, due to the increased costs involved and little market interest. As a result, smart bins are nowadays mostly implemented as a computing system *retrofitted* into existing bins. This may increase costs and create significant reliability issues in the operation of the system, since it is exposed to a severely harsh environment, including high temperatures; chemical reactions; and violent shaking.

A large number of bins is needed for servicing a city or an urban environment. These bins are often *placed unattended in public spaces*. Thus, they may be vandalized and require frequent replenishment. Furthermore, a computing system, either integrated or retrofitted in existing designs, can be an attractive target for theft due to the valuable components it may contain (e.g., advanced electronics, metals, and batteries).

B. Actual Status Information Collection

The collection of actual status information from each and every waste bin at an urban scale poses significant challenges. A simple solution is to equip each bin with a sensor node and a long-range communication unit, such as a cellular modem, and directly transmit information to the backend systems for further processing. Clearly, this option is not economically viable at urban scale due to telecommunication costs. Furthermore, these nodes will need some source of battery and frequent recharge, either automatically (e.g., via a photovoltaic panel) or manually (e.g., via frequent visits by service personnel). Also, radio coverage is not guaranteed throughout a city terrain. Tests must be performed at each bin location and iit may be necessary to move the bins to new locations.

A second approach is to take advantage of any available city network infrastructure, such as public WiFi hotspots, and use them as gateways to connect the sensor nodes with the backend systems. This cuts the long-range telecommunication costs but still an urban-scale network of sensor nodes must be installed and tested for connectivity with the gateways. In case there is no sufficient coverage at some areas, the authorities must install and maintain new infrastructure, incurring additional costs for procurement and network management at both the gateway and the sensor node levels.

A different line of thinking is to take advantage of communication units that roam around the city and collect information. These units act as mobile gateways or sinks for sensor nodes equipped only with low-power wireless communication units. The *garbage trucks* are a profound option, since they are already in the field. In case the trucks are already equipped with a fleet management system (FMS) unit, it may be possible to enhance the unit and include an interface for receiving and

transmitting all the information collected from the field unit (i.e., the waste bin or a nearby unit) since the last visit. In this setting, it is necessary to adapt the on-truck software and hardware, as for example to integrate an antenna and a network protocol stack for communicating with the field unit. Furthermore, it is required to either extend the backend FMS system to include processing of collected information or to implement interfaces for exporting to a waste management system. The garbage truck option does not come without limitations. The truck collects information about the already visited waste bins and not about the ones way ahead. This is more useful for collecting historical information and cannot be used to dynamically adapt the service plan.

In many cases, *city or public service vehicles* roam around the city. Examples include municipality patrol service; public transportation like buses, trams, and trains; post office and courier services. These vehicles could be used as mobile sinks and transmit collected information either in real-time through a cellular network (if they already have Internet access for business operations) or once they connect to a WiFi hotspot, either while on the go or when they return to their depot after completion of service. Such vehicles can cover large parts of the city and provide fresh information. The large periods of disconnections and the opportunistic nature of connectivity episodes with both the sensor nodes and the Internet gateways poses significant challenges for application robustness.

The *citizen involvement* can dramatically increase the coverage, accuracy, and timeliness of information. Citizens' participation and contribution can transform their role from passive receivers of the waste collection service into active "*prosumers*" that both *produce* information *for* the service and *consume* information *of* the service with the aim to improve the quality of the received service. In contrast to the aforementioned approaches, the citizen involvement leads to manual rather than automated information collection. How to successfully motivate and reward participation remains an open discussion in the literature and heavily depends on the business models of the service provider. Due to this, we focus our discussion in the following sections on the automated collection systems.

III. Literature Review

A. Fill Level Sensing Prototypes and Architectures

A prototype waste bin system was constructed for the city of Pudong, Shangai, PR China [4]. The system consists of two parts. The first part is installed in the bottom of the waste bin, occupying about 20% of its storage capacity. This part contains the battery and the GPRS communication system. The second part is installed in the lid of the bin and contains a photo camera, a PC104 with 12 VDC supply, three LEDs and temperature and humidity sensors. The system takes photos of the inside of the bin (LEDs are used as flash to enhance the contrast). The photos are sent through GPRS to a central server for processing and bin fill estimation.

A less bulky system was constructed in Malaysia [10]. The waste bins are equipped only with a passive RFID tag with a range of 6 meters. The garbage trucks are equipped with an RFID reader, a GPS receiver, a low-resolution camera, and a GPRS connection. Once the truck stops nearby the waste bin, the RFID reader reads the tag of the bin and activates the camera to take a photo of the surrounding area ($3 - 6\mathrm{m}^2$) before and after waste collection. The photos are then sent to a central server that uses image processing and estimates the volume of waste inside and nearby the bin.

Fill level estimation can be realized with sensors based on a modulated infrared beam detected by a photodiode. The accuracy of the measurement can be influenced by transparent objects, the reflection of light on object surfaces, the ambient light, and the dirt over emitter and detector surfaces. One solution is to use multiple line-of-view sensors in parallel and a majority decision system [8]. However, this results in increase of cost per bin. Another approach is to use hall effect sensors and count the times a waste bin is opened or moved. Under some (strong) assumptions and simplifications, the count can be used as a proxy for the amount of waste inside the bin [8].

The SEA project designed a smart bin prototype using an ultrasonic sensor and IDEA's ArgosD (TelosB) sensor nodes running a custom TinyOS 2.1.1 application. The smart bin connects with gateways that are based on the New/Linux OS. SEA proposes a three-layer architecture for information collection [11]. In the lower layer, short-range *single-hop* communication through IEEE 802.15.4 is realized to transmit fill levels. In the middle layer, gateways with both short-range and long-range modules (GSM/GPRS) are used to collect information from the sensor node and send them through IPv4 to the backend. Finally, in the upper layer, servers receive, store, and process the collected information.

A similar architectural approach is followed in [12]. There, two sensors are used: an ultrasonic for fill level and a load cell for weight. Sensed values are transmitted to nearby gateways installed in light poles. The design allows detecting removal of a bin through the lack of communication. An interesting idea explored in the paper is the need to promote the citizen participation in the smart waste process. A prototype application for Google Android smartphones is reported, through which citizens locate the closest bins that are not filled and they can associate their activity (loading of waste) with bin filling through scanning a QR code placed on the bin.

A three-layer approach is followed also in [13]. There, multiple sensors are used in the lower layer: ultrasonic for fill level, load cell for weight, temperature and humidity, hall effect and accelerometer for detecting bin cover open events. Sensed values and operational parameters, such as bin identity, date, time, and battery power level, are collected and transmitted when a cover opening is sensed. This way, energy-efficient, real-time fill level reporting can be achieved.

The EU FP7 OUTSMART project designed a mesh wireless sensor network for Berlin, Germany [14]. The project uses an ultrasonic sensor for fill level estimation and a wireless sensor network in mesh topology based on IEEE 802.15.4 for connecting nodes with gateways through *multiple* short-range hops. From the gateways, the information can reach the backend systems for further processing.

The EU FP7 Future Cities project[2] develops an urban-scale living lab in the city of Porto in Portugal. In the context of the project, the Municipality of Porto is developing an

[2] http://futurecitiesproject.eu/

innovative data collection system for monitoring fill level of garbage containers. Functional pilot tests will be run using buses as "data mules". Both sensor-node-to-bus and bus-to-cloud communications are based on IEEE 802.11 (WiFi). The latter utilize roadside units (RSUs) and WiFi hotspots already installed in the city of Porto[3].

The EU FP7 Straightsol project[4] streamlines charity collection (e.g., clothes and books) from donation banks installed in public spaces and retail shops. The project used an infrared sensor for fill level estimation (at 20% reported accuracy) and transmitted the information twice per day through GSM for scheduling next day's collection. A small-scale actual pilot included 37 donation banks, 50 retail shops, and 5 vans and resulted in an estimated 5% revenue gain [15].

B. Commercial Products and Services

Commercial products and services for estimating waste bin fill levels are also available. Most offerings use ultrasonic sensors, as they can provide more reliable measurements. Examples include Agora Energy (France), Enevo (Finland), Libelium (Spain), IGS Research (Spain), Trimble (USA), Urbiotica (Spain), and SmartBin (Ireland).

Communication with the waste bins can be classified in two main categories. The first is proprietary protocols transmitting at the license-free ISM bands (like 868 MHz or 2.4 GHz). These require nearby Internet gateways from the same company (Agora Energy uses Sigfox Ultra-Narrow Band, Urbiotica uses U-Sense and U-Box). The second is cellular protocols based on GSM/GPRS/3G (Enevo and SmartBin). Libelium offers systems that can be configured to work with both gateway-based short-range protocols (IEEE 802.15.4, ZigBee, WiFi) and direct, long-range protocols (GPRS and 3G).

Sending as little as 1 message per day, all these approaches claim a battery life of 5-10 years, even when using cellular communication.

C. Mixing RFID and WSN

Wireless sensor networks (WSN) and radiofrequency identification (RFID) are pervasive environments. The integration of these two pervasive computing environments results in reliable, energy-efficient, survivable, and cost-effective solutions for various applications. From an energy consumption point of view, in an ideal setting, the passive RFID tags use energy supplied by RFID readers, receive a query, power up the sensor, collect the measurement, and send back a reply. This is a battery-free setup that requires zero maintenance.

The Wireless Identification and Sensing Platform (WISP) is a first approach combining RFID tags and sensors [16]. A 1-bit accelerometer (sensor) is integrated in an Alien Technologies ALL-9250 EPC-compliant UHF RFID tag for a total cost of US$0.90 per unit. In comparison, battery-powered communication systems cost more than US$5.0 per unit. The sensed quantity is transmitted as part of the tag identity in a range of one meter. This is useful for tracking small objects in a house but cannot be utilized in an open-space, harsh environment, as the reader must be placed close to the tag. An improved WISP version is presented in [17]. The WISP now uses the whole 64 bits of the address space for transmitting sensed values. The platform is implemented in PCB rather than as an integrated circuit and uses two antennas: one for power reception and one for communication. The EPC transmission protocol is implemented in software for the MSP430 microprocessor. This approach departs from the traditional thinking of RFID tags as integrated circuits. A large storage capacitor (e.g., $10\mu F$)) is used to collect power. Once enough power is stored, a burst of activity occurs.

From an architecture point of view, there are several options combining sensors, WSNs, and RFID [18]. The key difference is how the communication with the backend systems is realized and the sensing requirements. A first option is to integrate sensors into the RFID tags (circuits) creating "sensor tags" [19]. These tags require an RFID reader to collect the sensed values. Due to the low power available and the integration capabilities, such devices usually integrate simple environmental sensors, such as temperature, light, humidity, and contact (magnets). A second option is to integrate an RFID tag within a WSN node. A combined device acting as a WSN gateway and an RFID reader is used to identify the nodes through the RFID tag and collect the measurements through WSN technologies. Yet another option is to use a WSN as to detect unusual activity and then trigger an independent (power-hungry) RFID reader to detect presence of specific tags or to limit search area for tags. The scenario could also work on the opposite direction; an RFID reader continuously monitors an inventory. Once a tag is reported missing, a WSN is awakened to collect field evidence (e.g., sound and images). An extended analysis of available company products and academic designs on integrating RFID tags and WSN for various application domains is provided in [20], [21].

IV. The Dynacargo Approach

The Dynacargo project considers urban solid waste collection as a case example of dynamic cargo routing on the go. This is an extension of the capacitated vehicle routing problem, where a fleet of vehicles (garbage trucks) with limited carrying capacity of goods (waste) service a number of customers (waste bins) and the aim is to minimize the total route cost. The Dynacargo approach introduces two important aspects: a) the exact waste bin fill levels may be unknown at the start of the service (*dynamic cargo*) and b) the optimization algorithm must be capable to compute on-the-fly a new service path (*dynamic routing*), while trucks are *on the go* and new fill level information becomes available.

The Dynacargo approach proposes a modular architecture consisting of four layers:

1) Field units, for sensing and storing information about waste bin usage and status.
2) Information collection units, for collecting and transmitting information to the backend systems.
3) Backend systems, for computing optimal routes dynamically based on available information and distributing related information.
4) Information consumption units, for accessing and utilizing information produced in the system. These include systems installed in garbage trucks for getting

[3]http://futurecities.up.pt/site/buses-used-as-date-mules-at-porto/
[4]http://www.straightsol.eu/

route updates, web portals, and mobile applications for citizens to get informed about service frequency, fill level, and notifications for service outages.

The most critical part for the successful operation of Dynacargo is the process design for collecting status information from thousands of bins. At this urban scale of bins, network formation and routing between nodes becomes unmanageably complex and devices with constrained sources of energy become very quickly points of failure and cause network partitions and node isolations.

The approach of Dynacargo is to utilize vehicles that roam around the city and network infrastructure that is already deployed. The system architecture is depicted in Figure 1. The vehicles are equipped with information collection units that act as mobile sinks for the sensors. The vehicles exploit communication opportunities via public WiFi hotspots already installed throughout the city or once they return back to their depots. If the vehicle has already Internet connectivity (e.g., in the case of a bus offering Internet access to its passengers through a cellular connection), this can also be utilized. Once an Internet connection is available, the vehicles send to the backend systems the status information they collected. Since there is no need to transfer the bin status information in real-time, the deferred delivery of information is acceptable.

The selection of appropriate technologies is a crucial factor for the successful deployment and operation of the system. Regarding the sensor nodes, it is a design choice to use only single-hop links between sensor nodes and mobile sinks. This choice offers significant benefits over multi-hop communications. Single-hop reduces *energy consumption* for constrained nodes that need not turn on their radio to receive and process packets by other nodes. The short range of node transmissions allows *spatial reuse* throughout the whole city. *Routing overheads*, in terms of protocol processing, energy consumption, and network traffic are avoided. There is *no single point of network failure*, as multiple vehicles cover the city. The design is characterized by *scalability and simplicity*, as new nodes can be added to the network with minimal effort and without affecting network capacity.

All communications in the system are opportunistic in nature. From the sensor node point of view, it is by and large unknown when one of the free-roaming vehicles will reach its vicinity and establish a communication link. Also, it is unknown how long the contact will last, since we do not assume that the vehicle stops moving at each and every bin. From the mobile sink point of view, it is again by and large unknown when and for long the free-roaming vehicle will be within the range of a WiFi hotspot and thus, if and how much information it will be able send to the backend systems.

In this environment of operation, there are challenges to overcome and tradeoffs to explore for an efficient function of the collection system. Examples include the range of operation for the sensor nodes (longer distances versus power consumption and interferences), detection of contact opportunities (always-on versus power-off periods for energy efficiency and missed communication opportunities), transmission costs (rich information versus power consumption), disruption handling (transmission of long packet sizes and fragmentation issues), and protocol stack complexity (protocols with large headers and rich functionalities versus simple packet structures and required functions).

In principle, we opt for a lean, modular, and scalable system and network architecture that can support the urban scale of devices that must be integrated. As requirements may emerge in the future, the modular approach allows system components and technologies to be replaced with ones providing richer functionality. In the next section, we describe the system architecture and design for the mobile sinks. The mobile sinks are the critical chaining component that supports the whole operation of the system.

V. Mobile Sink System Design

The Dynacargo information collection system has an adaptable, modular, and configurable design that allows optimizing its operation for multiple scenarios. The system is built using open-source software. It is based on a small-form-factor computer, consuming about 10 W of power (maximum) and having two USB 2.0 ports, built-in WiFi and Bluetooth, and one Ethernet port. It is supported by GNU/Linux and Google Android operating systems running from a microSD card.

A. Field Information Collection

The waste bins are equipped with ultrasonic sensors and active RFID tags. The active RFID tags transmit periodically their (waste bin) identity and a sensed value regarding its fill level. This option allows the minimal possible information to be transmitted periodically. All tags are configured to operate in beacon mode, broadcasting the information every few seconds in a range of about 100 meters. Active RFID tag transmission technology is much lighter in complexity and in coping with harsh environments compared to that of WSNs.

The mobile sink connects with an active RFID reader installed in the vehicle through Bluetooth or one of the USB ports. As the vehicle roams around the city, the RFID reader reads the tags and collects the information to the sink. Given the short "packet" size (less than 128 bits), the tag range (100 meters), and a realistic average speed of 40 km/h in a city, the tag must beacon at least every nine seconds to be read by the passing vehicle. At this rate, its battery life will be depleted in about 5 years, which is rather satisfactory. Increasing the tag range or allowing a more stochastic operation, as in the case that an area is covered by multiple vehicles, this constraint can be further relaxed.

The use of RFID technology allows reading multiple tags simultaneously (group of nearby bins), without collisions and re-transmissions, as it would be the case of a wireless sensor network. We note however that the mobile sink is not bound to RFID technology. If more status information must be collected per bin, such as multiple fill level measurements or measurements of different parameters, sensor nodes can be used, like ones based on IEEE 802.15.4 protocol. In this case, a USB port of the system can be used to plug an appropriate node and antenna. In this case, there are issues to be studied regarding to the detection of contact opportunities by nodes in an energy-efficient manner and the transmission of information [22]. In many cases, waste bins are installed as groups (rows) of bins or in proximity (e.g., opposite sides of the road). Further studies are necessary towards exploring energy-efficient policies for

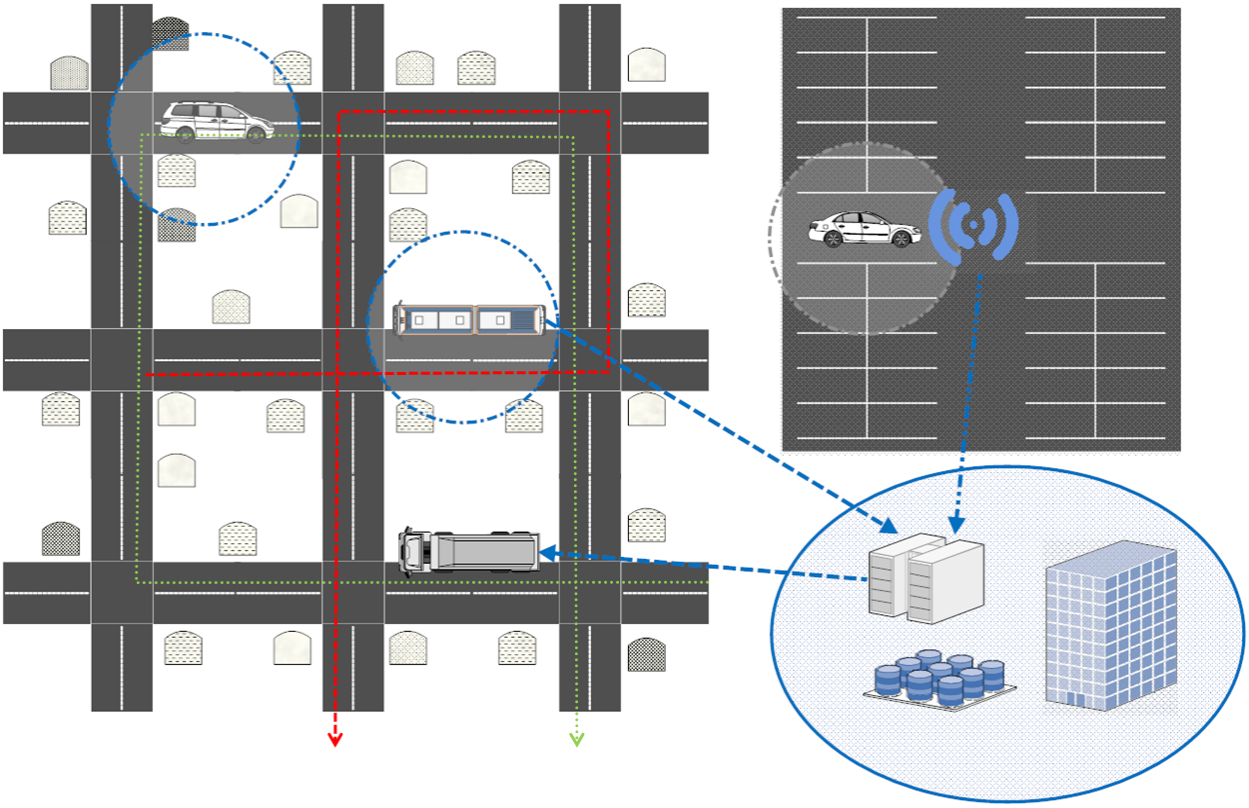

Fig. 1. The Dynacargo approach. Initial service plan (green line) optimized (red line) based on collected bin status information.

combined detection-transmission opportunities with low-duty cycles in such an environment: the mobile sinks may need to swap between beaconing and receiving information so as to allow detection of nearby bins that were not identified in first contact.

Initial simulations with Contiki-based sensor nodes, ContikiMAC, Rime protocol stack, and a mobile sink indicate that the node can detect contact opportunity and transmit information to the passing by vehicles even with a 1% radio duty cycle. This translates to significant energy savings that can lead to battery lifecycles comparable to those of RFID tags. Introducing more complex network protocols, protocol layers and stacks, or application-level logic at this stage of communication must be carefully considered and evaluated, given the episodic nature of communications [23]. Longer packets or complex processing can cause communication disruption and packet corruption, as the vehicle moves away from the bins. This translates in lost opportunities to collect viable information from the field and significant energy consumption for the sensor nodes.

B. Backend Communication

An application running on the mobile sink is responsible for receiving the information from the field units. As explained in the previous, we assume that the vehicle has access to the Internet once it returns to its depot or sporadically through any public WiFi hotspots available in the city. Handling the network issues arising in such an opportunistic environment at the application layer can be troublesome. Our approach is to build the mobile sink with a delay/disruption-tolerant networking (DTN) architecture. A DTN architecture allows extending network connectivity fighting large delays or periods of disconnection, where traditional Internet protocols cannot cope with [24], [25]. In the case of Dynacargo, a DTN protocol stack that places the Bundle Protocol (BP) on top of the transport layer is implemented.

The DTN stack is utilized as follows. The application collects status information from the field and is configured to send them to the backend system through the Internet. There are different options in realizing the application-to-stack communication. One is to develop the application using the DTN API (application programming interface) instead of the traditional network sockets API. Another one is to introduce a transparent DTN proxy/tunnel with one end lying in the mobile sink and the other end in the backend system. Yet another option is to use file interfaces and utilize already-available DTN-enabled applications for sending the files to the other end. The exact stack implementation (e.g., DTN2, IBR-DTN, ION) and tool choice is more a matter of personal taste and familiarity with the DTN technology.

The important aspect of a DTN approach is that the collection application succeeds in sending “immediately” the status information to the network, even when there is no network connection available. Then, the DTN is responsible for handling and restoring networking connectivity, coping with disruptions and bundle (packet) retransmissions, and temporarily storing the information in long-term storage, until a network connection is available. The DTN approach allows

to totally liberate the application from management tasks: it needs neither to handle connectivity issues (the network is always on) nor storage (the information bundles will be stored by DTN is necessary). The Linux operating system handles automatic connection with open WiFi hotspots and on top of that the DTN stack transmits to the backend system any pending bundles for further processing.

C. Concept Validation and Functional Tests

A prototype mobile sink is now implemented. The sink interfaces an active RFID reader and an application is developed that collects the readings and transmits to the backend systems through a DTN tunnel. The DTN functionality is implemented using the DTN2 software, customized and optimized for fitting the constrained resources available. Another instance of the DTN2 software runs on the backend systems in order to receive the bundles sent by the mobile sink. The storage in the sink is realized using a USB flash drive occupying the second available port of the system. This is necessary, as the microSD card will wore out very quickly if small files are written continuously to it.

The prototype system is tested in a controlled environment with emulated network disruptions. A system acting as a WiFi access point exposes a wireless link for random period of times. Upon detecting a WiFi link opportunity, the prototype connects through it to a public server (DTN endpoint) and unloads any collected information so far. A process running on the prototype creates at random point of time set of bundles, effectively emulating the collection of information from waste bins.

VI. Conclusions and Future Directions

The increasing population concentration in cities and urban areas creates the need for improved waste collection processes. Optimized use of available resources can be achieved by devising service plans based on actual fill level information. At an urban scale, the collection of status information from sensors installed in waste bins poses significant challenges in network setup and operation, both technical and financial. We presented Dynacargo, an innovative smart city application for urban solid waste collection. Dynacargo exploits already available network infrastructure, such as public WiFi hotspots, delay-tolerant networking (DTN) technology, and single-hop RFID-based communications in order to reduce costs, simplify system operation, and support scaling at urban level. We also describe a system design and the developed prototype of the mobile sinks carried on vehicles roaming around the city.

The proposed Dynacargo system will be pilot-tested in the Municipality of Nafpaktia in Greece. The Municipality has an area of 870.38 km^2 and a population of 27,800 people (in 2011 census). Eleven municipal trucks are used for waste collection from the bins. There are about 2,100 solid waste bins installed in about 140 settlements, villages, and towns in the area, including urban, suburban, and rural areas. The pilot tests will allow gaining insights on areas of improvement and experiment with vehicle movement and network connectivity issues in a city terrain.

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