Organizing Network Management Logic with Circular Economy Principles

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***Abstract*—The traditional cycle of industrial products has been linear since its inception. Raw resources are acquired, processed, distributed, used and ultimately disposed of. This linearity has led to a dangerously low efficiency degree in resource use, and has brought forth serious concerns for the viability of our natural ecosystem. Circular economy is introducing a circular workflow for the lifetime of products. It generalizes the disposal phase, reconnecting it to manufacturing, distribution and end-use, thus limiting true deposition to the environment. This process has not been extended so far to software. Nonetheless, the development of software follows the same phases, and also entails the use–and waste–of considerable resources. This include human effort, as well as human and infrastructure sustenance products such as food, traveling and energy. This paper introduces circular economy principles to the software development, and particularly to network management logic and security. It employs a recently proposed concept–the Socket Store–which is an online store distributing end-user network logic in modular form. The Store modules act as mediators between the end-user network logic and the network resources. It is shown that the Socket Store can implement all circular economy principles to the software life-cycle, with considerable gains in resource waste.**

***Index Terms*—Circular economy; software development; network-application interaction; network management; security.**

I. Introduction

The development of computer software is a business of speed. As the real world gets mapped to the virtual one, more and more concepts, applications, tools, libraries and techniques appear and disappear in a matter of months or few years at best. Naturally, any software developer can see a pattern: the wheel gets re-invented and re-implemented periodically, spawning torrents of short-lived apps in the process. If we study the sub-field of network management and control software, the situation is further aggravated by the fast-paced changes in the underlying hardware platforms. The Cloud, 5G, virtualization, resource slicing and IoT are but a few of the terms that where introduced in the past few years.

Expectedly, surveys identify that a 66% percentage of queried IT specialists acknowledged difficulty in keeping up with advances in the networking field [1]. We can infer that this ratio can be higher for application developers that do not specialize in networks. Under these conditions and the push for fast production cycles, we can safely assume that the ecological planning of resources is wither downplayed or completely disregarded.

The consequences of roughly designed software has direct and indirect ramifications to the economy of resources. Directly, the produced software manages the modern world. If the produced network code is energy-consuming, error-prone and insecure it will not only waste network resources, but will also cause resource waste in the real world. Indirectly, the software development process is not for free. Developers need to devote person-months for a single product aspect. Human sustenance resources must be expended in the process, including food, transportation and climate conditioning. Therefore, bad or repeated software design translates to waste of such resources at the very least. Moreover, the supporting network and computing infrastructure is always on, leading to energy and maintenance resource consumption.

This work proposes the use of the Socket Store as a means of implementing circular economy in the computer networking software market [2].The Socket Store is an online repository of end-client network logic modules. Within the Store, network providers expose the infrastructure capabilities, and researchers publish reusable, end-client software modules that operate on top of them. Developers purchase access to modules fitting their application, and simply invoke them transparently via a simple, Berkeley sockets-inspired interface [3].

The Store can transform the software life-cycle by altering the disposition phase as follows:

- From disposal to re-acquirement. Modules in the Store are used, evaluated, ranked, and commented upon. This enables subsequent buyers to make more educated choices in network modules incorporated to their software application.
- From disposal to re-processing. Modules in the Store can be freely and intuitively re-combined to create new ones that meet specialized application needs.
- From disposal to re-distribution. The Store remains a distribution point for all marketed modules. Disposal pertains only to modules that have proven inefficient and their contributor failed to maintain them properly.

These three general alternatives to the disposal of products are the pillars of circular economy, a new concept which makes a case for ecological product design [4]. According to it, the design refers to the complete life-cycle of the product and its effects on the environment, rather than just to its intended end-functionality. As described in the following, the Socket Store allows for the aforementioned alternative approaches to disposal, constituting an ideal vessel for enforcing circular economy to software development.

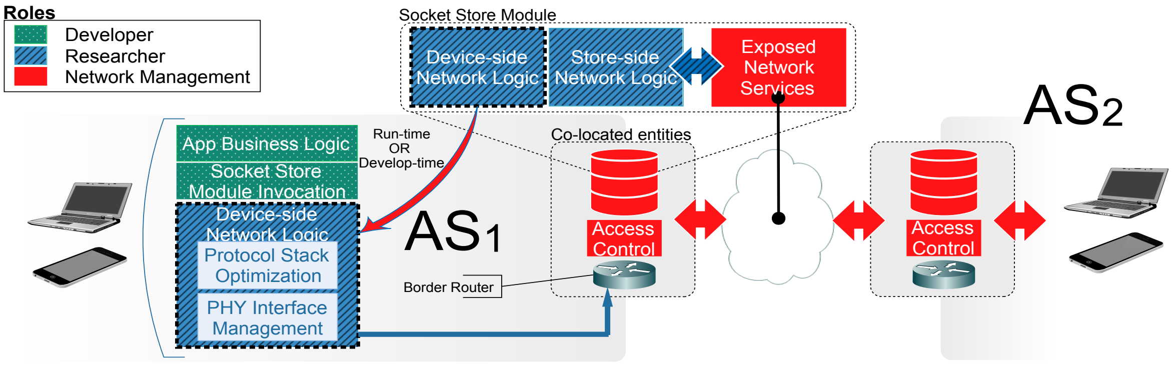

Fig. 1. Overview of the Socket Store operation principles and associated roles.

II. The Socket Store Concept

Overview. Figure 1 presents the components comprising the Socket Store concept, their general placement within the network and the jurisdiction they fall into. The description of the Socket Store will revolve around three involved roles, namely the mobile/desktop app *developer*, the networking specialist (*researcher*) and infrastructure provider (*network management*, e.g., ISPs).

The Socket Store proposes a clear separation of roles pertaining to the programming of end-devices (mobile phones, laptops, desktops, sensors, etc.). The developer remains responsible for designing and implementing the business logic (i.e., intended function) of an application. Communication capabilities required by the application business logic are delegated to Socket Store modules. Access to these modules is obtained (*purchased*) by the developer during the implementation of an application, in a manner reminiscent of app stores (e.g., Google Play). In other words, we assume the existence of a module-browsing front-end (e.g., a web-based GUI), where the developer can search for and obtain modules. Purchased modules are invoked by the developer via an interface based on the well-known Berkeley sockets. A module offers sophisticated functionality, security or performance, without further coding burden for the developer.

The modules can be considered as the agents that are responsible for mediating between an app and the network resources. We use the term resources to describe any programmable or parametric network function, exemplary ranging from packet schedulers, congestion protocols and flow path deployment to advanced QoS, middlebox access, network state monitoring and on-demand creation of virtual infrastructure. The Socket Store is essentially the distributed software platform that hosts modules and handles their lifecycle, comprising construction, instantiation, distribution and destruction.

The modules are designed and implemented by researchers. Their scope is to provide a communication functionality while optimizing a clearly specified performance objective. The offered functionality can range from generic (e.g., packet jitter control) to specialized behavior, e.g., real-time high-quality multimedia transmission. The performance objective can exemplary express QoS requirements (e.g., packet latency, loss rate, multimedia quality), device resource expenditure (e.g., CPU or battery quotas) and allotted network resources. Moreover, the network-side optimization can encompass network-wide concerns (e.g., load-balanced access to network resources), apart from user-specific optimizations. The publication of new modules to the Store is intended to follow the scientific publication process: eponymous submission followed by a revision round by experts and an open commenting/ranking system.

Module design. A Socket Store module comprises two separate but closely communicating components, responsible for *device-side* and *network-side* optimization respectively. The device-side component is responsible for carrying out advanced processing of packets and data flows (e.g., scheduling, adaptive rate control, backup and fail-over), perform protocol stack optimization (e.g., choose between IPv4 and IPv6 in terms of latency [5]) and manage multiple physical interfaces (e.g., cellular and WiFi) for load-balancing, redundancy or QoS [6]. The device-side component is downloaded to client devices during development, or automatically upon app installation. In the first case the developer is simply supplied with a code library during the app development. The second case can optionally employ a Transferable Object (TO) paradigm (detailed in the next subsection) [7], which mimics the way app updates are distributed from App Stores. This approach is intended to allow for transparent network module updates, localization (e.g., per Autonomous System attributes) and minimal developer coding burden.

Upon invocation (e.g., on app start-up), the device-side component contacts the Socket Store in order to create an instance of the corresponding network-side component(s). The network-side component then allocates the necessary network resources in communication with the network management. In a Software-Defined Networking environment for instance, the network-side component of the Socket Store module can proceed to setup app-specific routing by interacting with the corresponding controller. Another example is the creation of Network Virtual Function chains that are required by the app business logic. Upon app termination, the network-side component releases the allocated resources (e.g., back to a resource pool), while the device-side component frees client-

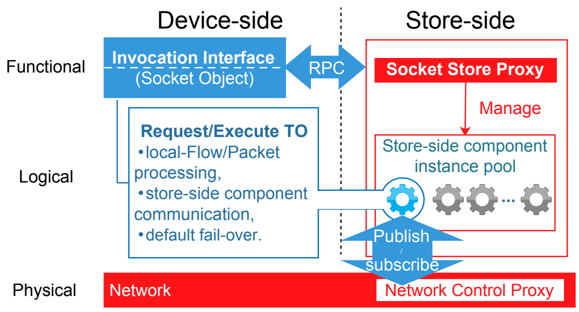

Fig. 2. Overview of the Socket Store components and communication.

side resources.

Notice that a module may not implement both the device-side and the network-side component, but rather adopt a default instead. This capability allows for modules that target exclusively device-side or network-side optimization. The default device-side component simply redirects the app traffic to a Store. The invoked network-side component then acts as a mediator for the traffic, meeting a network-side optimization objective. In absence of a network-side component (i.e., device-only optimization), the app traffic simply defaults to not receiving special treatment from the network.

Hosting and access. The network management is responsible for: i) physically hosting the Socket Store, ii) performing access control to the Store, and iii) exposing interfaces that allow for the interaction between the modules and the network. Given that the Socket Store may act as connectivity mediation point for end-user apps, its physical position within the network is significant. In the inter-AS case, the Stores should then ideally be co-located with AS border routers. Since the app traffic needs to cross the AS borders in any case, co-locating Stores and border routers yield no additional path hops. In the intra-AS case, Stores should be placed at central topology points for similar reasons.

Finally, we outline the scope of the Store access control. Given that modules are purchased by developers, there may be a need to license and authorize their use from the end-users. In the general case, the modules are distributed in the context of an app, either directly or as in-app purchases. Therefore, module access authorization can be delegated to mobile App Stores. Thus, owning an app also grants access to the corresponding Socket module(s). It is noted that licensing per device is also possible in principle. In this case, the device-side module components tie their operation to physical device characteristics by enforcing Physical Unclonable Functions (PUFs) [8]. The Socket Store access control is also the point for incorporating defense schemes against Denial-of-Service attacks targeting the Socket Store.

A. Architectural Aspects

We proceed to study the structure of the Socket Store module components, the exposed network services and their interconnection.

The system modules follow an object-oriented approach, while their inter-communication employs the well-known Remote Procedure Call (RPC) and Transferable Object (TO) patterns [9]. As shown in Fig. 2, the device-side component is an instance of the Device-side Socket Object class (DSO), which exposes a functional interface to the app developer. The DSO can be installed to the device in two ways. First, it can be received as an offline library during the app development and be distributed with the app. Second, it can be downloaded during the first-time initialization of the app (run-time). In this case, the DSO requests and receives the device-side network logic from the socket store in the form of a Transferable Object. A TO (also known as valuetype) is not a remotely referenced object, but is rather obtained by value and resides at the device-side [10]. The TO is subsequently stored locally for future use (until an update occurs). Its execution instantiates the device-side network logic of the Socket Store module, which encompasses device-local packet/flow processing and contacting the network for the allocation of resources. The TO logic is not intended to follow a strictly defined workflow. For instance, a DSO may run on top of multi-path TCP capabilities offered by the underlying device operating system, or implement this functionality itself via proper management of a plain, Berkeley socket pool [6]. The DSO destructor signals the network to de-allocate resources. In case of failure during the TO acquisition or execution, the DSO can default to the normal network behavior (e.g., instantiate a plain Berkeley socket to the intended destination).

The Store-side component is also an instance of a socket object class (SSO). The SSO instances are created by the Store, after an invocation from the device-side code. Their role is to interact with the exposed network services, allocate resources (such as paths) and react to their modification. The SSO instances are managed by the Store Proxy, following existing distributed object management approaches [11]. Should a DSO signal its destruction (or has remained inactive for a given timeout), the Proxy returns the SSO instance and its associated network resources to a pool for re-use, or destroys the SSO instance and frees the related network resources. The decision is meant to be adaptive, depending on the popularity of the Socket module in question.

The communication between the DSO and SSO, as well as between the SSO and the network control follows an event-driven approach, implemented on top of Remote Procedure Call pattern. The DSO and SSO mutually expose interfaces to their internal functions. The form of these interfaces can be defined by the researcher, who is responsible for designing both components. Moreover, the related functions should be designated as private and final, to denote that their callback or modification from the developer is not intended. The communication between the SSOs and the Network Control is also event-driven, following a publish-subscribe approach. Particularly, the Network Control publishes events pertaining to the status modification of network resources, e.g., a change in the end-to-end latency of an allocated path. An SSO subscribes to the event types related to its operation and implements the handling code that should be executed once they are triggered. At the network layer, the RPC-related

```
Initialization /* On device or app start-up. */
sIPs←obtain_store_IPs()
foreach purchased module m do
  | update_TO(m) /* Authorize and download TOs. */
end
Connection Establishment
Input: protocol, ip, port,{module_id}
Output: Connection object c.
to←retrieve_local_TO("module_id")
c←to.execute() /* Also invokes store-side module. */
if c.invalid? then
  | c←LegacySocket.new(protocol, ip, port)
end
Utilities
c.send(data)
c.close() /* Release device/network resources. */
Exposed Events
OnReceive(data)
OnConnectionFail(fail_type)
```

TABLE I

SOCKET MODULE BASIC INVOCATION INTERFACE AND FUNCTIONALITY AT THE DEVICE-SIDE (DSO).

signals can receive special treatment from the network. Next, we detail the structure of DSOs and SSOs.

The DSO structure. In software programming terms, the DSO is a class instance whose basic structure and functionality is given in Table I. During the *initialization* phase (app run-time), a DSO retrieves the Socket Store network identities (IPs). Subsequently, the DSO proceeds to check for TO updates, in which case it obtains (after proper authorization) and locally stores them. In order to minimize the overhead of this process, the TO updates can occur at the same time as app updates, e.g., periodically or per OS start-up. *Connection establishment* comprises the retrieval of the corresponding TOs from the local storage and their execution, which returns a socket connection object. We note that a string identifier ("module_id") is supplied alongside the usual connection parameters (protocol, port, ip) as an optional argument. This identifier, which is produced by the Store, corresponds to a specific parameterization of the related SSOs. Its goal is to hide unneeded parameterization complexities from the developer. In case of any error, the connection effort reverts to establishing a plain Berkeley socket (LegacySocket) instead. The outcome of the connection can be handled within the DSO code via type checking. (I.e., checking if the connection attempt returned an object of the class LegacySocket). Finally, notice that the outlined logic also holds for binding a local port/interface for receiving incoming connections (apart from connecting to a remote destination).

The returned connection object offers a Berkeley socket-inspired interface at a minimum (e.g., supporting the `send()`, `close()` functions etc.), which constitutes common knowledge to developers. Moreover, a DSO can offer additional *utilities,* depending on the objective of the module as a whole. For example, a multimedia streaming-oriented module may overload the original send function to directly stream video files, e.g., `send(AVIFileStream)`. Another example could be a Delay Tolerance-oriented module [12], which

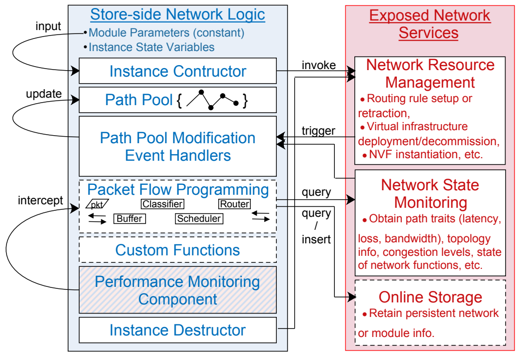

Fig. 3. Schematic of the components comprising the store-side network logic of a module instance (SSO), and their relation to network services.

adds functionality for `UndoSend()`, `RedoSend()`. Lastly, the DSO exposes events, such as incoming data, failure to uphold a performance objective, etc., which should be handled by the developer. **The SSO structure**. The schematic of the SSO structure and functions is given in Fig. 3. SSO also follows an object oriented approach, with a constructor, a destructor, member functions, parameters and variables, which can be marked as private or public, etc. The parameters are represented as *constants*, and each separate parameterization is mapped to the string identifier "module_id" described earlier. The instance variables are accessible from the SSO member functions and are mainly responsible for expressing the internal state of the SSO instance. The SSO constructor is responsible for contacting the network control for allocating required resources (e.g., path, VPN, firewall deployment). The SSO destructor is responsible for de-allocating these resources when triggered by the DSO (or after a timeout).

During its development, the SSO subscribes to the network events that it should react to. The Network Control (state monitoring service) is responsible for publishing these events, eventually triggering the subscribed SSO event handlers. An example is given in Fig. 3 in the context of the `PathPool` programmatic facility. `PathPool` is a high-level collection of `Path` objects, each corresponding to a path allocated to the socket module. The `Path` object facilitates programmatic query of path traits such as latency and bandwidth of intermediate links. Should, e.g., the latency of a link change, the network monitoring service triggers the corresponding subscribed events at the Store. The SSO path event handler is triggered if its `PathPool` is affected by the change in the link state.

SSO can operate at flow-level granularity, in which case it operates only when the app-specific network routing should change. Nonetheless, advanced socket modules (e.g., novel schedulers) may require processing at pack-level granularity. The SSO supports this functionality by supporting packet-flow programming [13]. Nonetheless, packet-level processing is generally computationally intensive, e.g., requiring the processing of packets at user memory space [14], or via programmable hardware (e.g., FPGA [15]). Therefore, such functionality should be considered when pricing a socket module. In both cases, however, the network management should provide facilities for module *performance monitoring* (e.g., libraries for monitoring the end-to-end latency). The module monitoring is required for deducing whether its performance objective is being met, and also for objectively ranking competing socket modules.

Finally, we outline inter-Store and Store-Cloud interactions. Inter-store communication can employ modules, i.e., each SSO can also act as a module client and call upon other socket modules. SSOs can also interact with online storage services to facilitate the module operation. For instance, a DTN-oriented socket may store pending packets in the Cloud, until the connection end-point becomes available.

III. Potential and Challenges

The Socket Store allows for a clearer separation of concerns among app developers, researchers and network providers. Apart from the envisioned motives mentioned in Section I, the Store concept can provide additional potential. Firstly, it could bring the functionality of novel networking paradigms to the end-users. For instance, socket modules could provide a Named-Data Networking interface to developers [16], allowing for an "Interest" and "Data"-based communication while hiding underlying network operations. A similar approach can be followed for the Recursive Inter-Network Architecture (RINA) [17], which models networking as inter-process communication. The Store could also serve as an end-user access point to novel schemes that aim at providing QoS in inter-AS routing [18]. Secondly, the Store provides the network management with direct knowledge of the users' requirements and intentions, limiting the need for indirect monitoring and enabling network-wide resource optimization. Lastly, the proposed scheme can constitute a platform for visibility and fair comparison of research contributions. Automatic evaluation and ranking of novel schemes is possible, exploiting existing public testbeds in the process [19]. The main questions in our future research agenda are:

Interface optimization and evolution. Apart from the described approach, is there a more efficient way for interfacing among devices, the Stores and the Network? What would be the decisive performance metrics? Can we ensure inter-Store compatibility and interface extensibility?

Developer usability. How can a developer search for a module that fits his app needs easily and effectively? Is there an effective way of bringing this facility directly inside app development environments?

Market model and pricing. What should be the purchase and pricing model for socket modules? Purchase access once per app (or enable as in-app purchase), or charge per usage? How can we monetize the value of network resource access in a rational and automatic manner?

Deployment. Socket Store instances are required in the vicinity of clients. What network-intermediate points of deployment are needed (e.g., at IXPs)? What factors should drive an incremental deployment strategy?

Security. Which are the new attack vectors that are introduced by the Socket Store? How can we enforce security and privacy in the communication between the involved entities?

IV. Related work

Building network-aware apps and application-aware networks has constituted an early, notable research goal [20]. Nonetheless, to the best of the authors' knowledge, there has not been an effort to make research knowledge modular and reusable, with a consistent interface between the network and the applications.

Network-side. In 1998, Lowekamp et al. proposed the REMOS unified network query interface, which allowed applications to request network topology and congestion information, in order to tune their behavior accordingly [21]. PerfSONAR is a more recent approach towards this direction [20], employing a more standardized metadata format for describing network characteristics [22]. The Unified Network Information Service [23], offered an alternative solution with scalability, security and performance benefits. Application domain-specific network querying solutions exist as well, such as MonALISA for distributed systems [24], and the Network Weather Service for meta-computing [25]. These approaches also employ standardized formats for representing the network status and configuration [26]. In Socket Store terminology, these works are means of exposing the network infrastructure capabilities, allowing researchers to build Socket modules on top of them.

Novel infrastructure capabilities, such as Infrastructure-as-a-Service, can be exposed in reusable component form at the Store via the NFV paradigm [27]. Additionally, the Store can benefit from directly interfacing with SDN technology, which already offers the necessary interfaces to query and modify the network state in a modular manner (e.g., network *intents*) [28]. Based on the advances in SDN and NFV, recent works have proposed new paradigms that can enable QoS guarantees across the Internet, crossing the Autonomous System borders [29].

It is also noted that the "store" term is also used for exposing network functions and services in a modular form (e.g., NFV stores) [30]. There also exist user-friendly online platforms for chaining such modules [31]. Since these works expose the network capabilities in an easy-to-use form, they also promote their interfacing with the client-side logic at the Socket Store. It is noted that network functions should preferably be exposed by the network providers and not by independent parties, to avoid code trust issues [32].

Device-side. Given that the Berkeley Socket API is popular among developers [3], researchers sought to preserve its principles while hiding complex network logic underneath it. Protocol optimization, packet scheduling and hardware interface selection have constituted notable optimization goals [6], especially for QoS monitoring and provision in mobile devices. Apple is also incorporating a transparent socket selection between IPv4 / IPv6 in its most recent OS revision [5]. Apart from device-side optimizations, there have been proposals for sockets that signal the network for the type of treatment they require [33]. Similar approaches have been proposed for the transparent evolution of the TCP protocol [34], and multipath TCP and HTTP constitute notable cases [35]. The recently started IETF Transport Services working group targets the API standardization of socket augmentations [36].

Within the Socket Store, such works can be freely published as reusable modules and become accessible to developers. This access can be readily uniform and transparent, with trivial coding overhead [7]. The Berkeley API is retained as the basic interface. Finally, the Socket Store is the point where the two ends-the device and network states-can meet, allowing end-users to benefit from their interaction.

V. Conclusion

The present work proposed the use of circular economy principles in software design. To this end, it proposed the use of the Socket Store, a novel approach for realizing network-aware applications and application-aware networks. The Socket Store makes network logic available for purchase by developers, who can combine and incorporate them to their applications. It naturally acts as a platform that enforces software re-distribution, re-processing and re-use. These traits align the Store perfectly to the principles of circular economy, making for educated, ecological and proper use of human and raw resources, while allowing for fast-paced software development.

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