Research Statement

Ioannis Papapanagiotou

My *current and future plans* include investigating problems in the areas of High Performance Network Deduplication Systems, Cloud Computing, and the Internet of Things. My grad students and I work ambitiously to bring interesting ideas to mainstream practice. My research is based on a three-step approach: (a) identify a unique engineering problem in the aforementioned domains; (b) develop the appropriate theoretical framework; (c) evaluate through simulation, emulation or prototyping. In what follows, I will cover my ongoing projects, my vision and my research accomplishments.

1 Current Projects & Vision

1.1 Cloud Computing

My first project involves designing Infrastructure as a Service (IaaS) architectures with guaranteed performance Service Level Objectives (SLOs). The SLOs play a crucial role in cloud services as they are based on provisioning resources on demand, otherwise known as cloud elasticity. The goal of this project is to investigate central orchestration techniques such that the performance of both the compute and the storage services are optimized.

In our first work [25], we designed an SLO-aware resource scheduling for cloud storage systems in which we achieved a 20% improvement in performance violations, with fewer storage nodes, and higher throughput per backend system, compared to the default scheduler in OpenStack Cinder project. We extended this work taking into account multiple volume requests per second and multiple backend systems [26]. We showed that the proposed scheduler can guarantee performance SLOs even in a dynamic workload, increase the I/O throughput of the volume that have been already provisioned in the backend systems, scale to a higher arrival rate for the volume requests, and finally minimize the number of active hosts (or else the energy consumption). The volume placement process is based on an APX-hard multi-dimensional Vector Bin Packing (VBP_d) algorithm. In order to reduce the complexity we propose a heuristic named Modified Vector Best Fit Decreasing (MVBFD). Our scheduler design for block storage systems is based on the principles of the OpenStack's Cinder scheduler.

My future vision is to extend this work towards enabling (i) batch-scheduling for multi-tenant architectures (e.g. our proof of concept will use the REST API of OpenStack), (ii) optimized cloud orchestrator with SLO guarantees. The optimal allocation of the virtual resources will be decided through an optimization orchestrator, i.e. maximizing a utility function $u_i = f_i(N_i)$ that will adapt multi-service allocation for each application α_i. N_i will be the virtual resource allocation vector of application α_i. Moreover, we are looking in several applications of the Cloud computing such as healthcare [3]. Part of this work is sponsored through a NetApp Faculty Fellowship.

1.2 High Performance Network Deduplication

The increasing demand for faster networks in the High Performance Computing era is outpacing the ability of the carriers to upgrade their Tier-1 infrastructure. The importance of building this needed infrastructure, such as 100Gbps networks, has been identified by DOE [5], while key research labs, such as Lawrence Berkeley National Laboratory, are currently looking into pathological problems of networks such as the Energy Service Network (ESnet). Recent work highlighting the efficiency problem has shown that utilization can be as low as 5% for files of size of 1MB, and as large as 50% for files of size of 16MB. A potential solution can be the implementation of Data Redundancy Elimination (DRE) systems, which can identify and remove duplicate chunks of data [23]. However, such systems have only been deployed in an enterprise

low-bandwidth setting. In my work [9], I have shown that DRE systems cannot currently handle traffic at the Gbps scale, because of bottlenecks that occur due to CPU and persistent storage space capacity constraints [4]. At high-bandwidth links, DRE systems may also also impose an extra delay due to TCP retransmissions. I have also demonstrated that Web proxy caches are inefficient in some scenarios due to the Zipf Law property of Web objects [8]. Nonetheless, I believe that a DRE system redesign can fundamentally increase our ability to solve current network limitations. *My research goal is to develop the foundation and advance the knowledge in the area of high performance computations for in line network processing.*

Hybrid Byte Level Caching: Towards this effort we first designed a hybrid level cache. Our trace driven analysis showed that some applications are more prone to packet-level deduplication, whereas others cannot benefit from deduplication (traffic through VPN). Hence, I designed and patented an apparatus that uses an intelligent scheduler to decide the optimal deduplication strategy [1, 2]. The proposed implementation showed more than twice as much savings compared to standalone proxy caches, and higher savings compared to byte caches. It also required a third of the memory to store the hashes, and provided a system speedup equal to two [9]. Several additional optimizations were also identified and filed numerous patent disclosures in this area with IBM.

Our current work focuses on redesigning the DRE systems and deploy them at a university network using Commercial Off the Self (COTS) hardware. I take the following principles into account in my in-line network processing design: (a) encoding performance - the speed of calculating the encoded or redundant data; (b) decoding performance - the speed of recalculating data or coding information following one or more packet losses; (c) easy of implementation - the complexity of the technique; (d) cost of implementation - licensing issues, as many coding techniques are patented; (e) interoperability - across multiple vendors or backward compatibility with current implementations.

1.3 Internet of Things

The third topic of my current research is around the Internet of Things (IoT). I am focused on two directions. The first is the secure communication of the Vehicular IoT. The car receives messages through local sensors, vehicular networks (inter-vehicle communication), and other connected entities. In this situation, the communication has to be secure, fast, and reliable. For instance, consider a group of autonomous vehicles driving on a high-way at high-speeds. Once a vehicle brakes suddenly, this should be broadcasted to other vehicles to avoid collision. It is critical to ensure the authentication of such messages to prevent an attacker from injecting/manipulating messages. If the delay introduced by the authentication operations is comparable to the transmission delay, then a car may not be able to brake in time. In this recent project, we develop Hardware-Accelerated authentication schemes that enables practical realization of cryptographic signatures for vehicular networks. Our system is based on Multi-Processor Systems on Chip (MpSoC) and we are able to provide significantly faster calculation of signatures with the same level of security. This work is ongoing.

The second part of this work focuses on the implementation of the IoT in Smart Buildings. We are currently looking into technologies like Geofencing. Geofencing is a Zone Based Location Based Service (LBS) which defines a virtual fence around a certain Point of Interest. In order to be able to provide any type of geofence based service in a smart building the accurate information of the microlocation must be known. However, there has been little innovation in the microlocation area. Hence, we are looking into techniques such particle filtering, and extended Kalman filters. Our recent work is published in [28] and in the IEEE IoT Journal [27]. Gimbal has provided a number of iBacons to support our work.

2 Past Projects

2.1 Network Data Analytics

This work was performed while I was working in IBM TJ Watson Research Center. We devised and patented an Operating System (OS) fingerprinting methodology that identifies each device type such as iOS, Android, BlackBerry, Windows, Mac OS X and Linux. More specifically, this methodology uses association rule mining to determine a potential correlation and trustworthiness of several protocol headers. I prototyped and deployed this idea in two wireless campuses, namely NC State University and IBM TJ Watson Research Center. The former included mostly student smartphone devices, and the latter corporate laptops. My

technique was able to accurately identify 98% of the devices in both networks [13], a figure that higher $10-20\%$ from other state-of-the art OS fingerprinting techniques.

Differential DHCP lease time: I investigated the impact that new types of wireless devices, such as smartphones, have on DHCP. I used two one-month long traces, collected at the gateway of NC State University and IBM TJ Watson Research Center, and compared side-by-side their DHCP usage patterns. I showed that DHCP implementations vary among device types, and have an effect on DHCP lease durations. To improve network address utilization, without introducing any protocol changes, I proposed a new leasing strategy which takes into account the device types. This strategy, compared to current approaches, provides a sixfold improvement in the address utilization without considerably increasing the DHCP overhead. My work was presented in ACM IMC 2012 [13] and granted a patent [7, 6].

Web Traffic: In this work, we focused on the areas where the traffic between mobile and laptop is different. More specifically, we looked into video delivery as it was the bulk of the network traffic requested by the end-user. Using the traces collected in the aforementioned locations, we studied the effectiveness of the device caches, as well as the effectiveness of the proxy caches. We showed that smartphone caches are not effective at all. Hence, we proposed caching polices for smartphone devices in which only a 10MB cache would provide the maximum achievable savings. In addition, we showed that there would be an considerable improvement in the Service Provider's bandwidth if proxy caches would be able to handle partially downloaded objects. My work was presented in ACM SIGMETRICS 2012 [14].

2.2   Functionality Distribution in Aggregation Networks

This work was performed in collaboration with Cisco Systems. We used Operations Research principles in the area of network design & dimensioning problems. This work was motivated by the lack of established principles on the design of next generation aggregation architectures, which have a tree structure. Specifically, most of the design problems address the issue of deploying new infrastructure. However, the cost to build out new infrastructure may be prohibitively expensive. In addition, vendors have introduced multipurpose edge "systems" (backplanes) that incorporate different functionalities in modular "sub-systems" (line cards). Finally, Internet Service Providers (ISPs) have to deal with the explosion of video traffic in different formats, e.g. multicast, peer-to-peer, mobile etc. Hence, it was of vital importance for the ISPs to re-engineer their infrastructure to meet these challenges. Moreover, Network Design Problems (NDPs) have to be revisited to include those multipurpose edge systems, instead of single-functionality devices (such as L2 switches or L3 routers).

Considering the above challenges, we developed a network design model that goes beyond the well investigated *location* and *dimensioning* problems. Our modeling approach is applied to both designing an aggregation architecture, as well as upgrading the current infrastructure. We proposed models based on edge "systems", rather than network elements. Edge systems may support different types of intelligence, either as part of the backplane or as part of the modular "sub-systems", i.e. high-end line cards. Finally, I evaluated the model with two close-to-real-life scenarios and multiple traffic profiles, based on data provided by EU ISPs. My results yield that ISPs will benefit from distributing the functionalities closer to the subscriber. Furthermore, sensitivity analysis suggested that ISPs should invest on systems that support more line cards and interfaces, rather than on devices with higher bandwidth. Our work was presented in IEEE CCNC 2010 [10] and was published in the IEEE Transactions on Network and Service Management [11].

2.3   Performance Analysis of Wireless Networks

Finally, I worked with analytical decomposition of wireless protocols. Specifically, I studied the Quality of Service (QoS) in WiFi networks (IEEE 802.11e). The motivation for this study was twofold; first, some IEEE 802.11e properties were not properly captured by prior analyses, and second, the current standards do not define principles for strict QoS [18, 24]. I used three common analytical approaches for wireless networks, namely Discrete Time Markov Chains, Closed form Queueing networks, and analysis using elementary conditional probabilities. I proposed several enhancements that included (a) QoS class differentiation, (b) Block-Acknowledgments, as defined in the IEEE 802.11e standard, and (c) erroneous channel conditions. I demonstrated that Block-ACKs may improve the QoS under erroneous channel conditions [15, 16]. I also proposed a methodology to incorporate non-markovian traffic to the analytical approaches. In addition, my

colleagues and I devised a scheme that combines TDMA for the VoIP class, and CSMA/CA for the rest of the QoS classes [21]. Our analytical results indicated that the saturation throughput was higher and the end-to-end delay was lower. Moreover, we showed that with the proper Admission Control, the aforementioned scheme may provide QoS guarantees [22]. We verified all these results through Discrete Event Simulations. We also extended the simulation analysis based on a Response Surface Methodology (RSM) in order to determine the effect of parameters from multiple layers of the network architecture in the performance of the wireless client [12]. During my collaboration with the VTT Research Institute, I also applied the same analytical approaches on the energy consumption of WiMAX networks (IEEE 802.16e) [20, 19, 17].

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