Summary

The reliability and performance of data centers play an essential role for the success of plenty of today's business and entertainment activities, while heavily depending on the effectiveness of the employed monitoring solutions. Data center operators need the ability to accurately monitor and dissect the behavior of their networks, while the tenants of distributed cloud-native applications also strive for pervasive monitoring intelligence to understand application performance.

Unfortunately, the rapid increase of networks scales and link speeds, and the radical transition from monolithic applications to microservice architectures, have significantly raised the expectations on both network and applications monitoring, as well as their complexity. With ultra-fast link speeds, network telemetry reports can contain millions of monitored events even on short timescales. Since a high monitoring timeliness and accuracy is often translated into an increase in the frequency and volume of telemetry reports, network monitoring can come at a huge overhead. At the same time, the multi-platform multi-layer distributed microservice design has increased the exposure of applications to failures, which also resulted into the explosion of the volume of application-level telemetry, ultimately leading to a significant data bloat issue for *cloud-native application observability*. Overall, monitoring at hyperscale is a problem still far from being solved.

In this thesis, a major effort has been devoted towards devising in-network solutions with the goal of increasing the monitoring performance for both the network and cloud-native applications, while keeping overheads and costs disposable. Towards this objective, we developed a set of sketch-based algorithms and systems, which helps to extract insightful statistics from high-speed data streams directly from programmable network devices, such as Protocol Independent Switch Architecture (PISA) switches and SmartNICs.

We first addressed the task of measuring the flow cardinality in a traffic stream, which is a common input to many fundamental network management tasks, ranging from attack detection to network planning. Specifically, we focused on turning some popular cardinality estimation sketches (e.g., HyperLogLog) into continuous-time sketches, i.e., add the ability to answer queries at arbitrarily time instants according to a sliding window model. Our proposed schemes allow overcoming the insensitivity to data recency of existing sketches, and enable better timeliness with minimal

interactions with a remote monitoring plane, due to the ability to continually compute real-time statistics directly in the network switches.

Despite their memory-efficiency, sketches are practically limited by the amount of SRAM memory available on a single switch, which is typically scarce for commodity hardware. Therefore, a second contribution relates to the collaboration of multiple switches to increase the accuracy of flow size estimation sketches. More specifically, we looked into the concept of disaggregated sketches, in which fragments of a logically single sketch are distributed across the switches. We focused on characterizing the interdependencies between the traffic patterns and the distribution of the measurement workload across the fragments along the flow's network path. We showed that the estimation accuracy can be significantly improved only by carefully choosing a subset of fragments to update.

In our final contribution, we complemented our sketch-based network monitoring suite with a new sketch-based framework for cloud-native applications observability. We tackled the observability data bloat problem by proposing a novel three-tier architecture to monitor cloud-native applications, which leverages the proximity of SmartNICs to the applications' microservices to mitigate the high overheads of observability. Our system stands out from the conventional observability tools by incorporating local metrics processing stages at every server within a sketch-based lightweight data plane running on SmartNICs. To the best of our knowledge, it is the first attempt to accelerate observability processing tasks through the offloading to a SmartNIC. As demonstrated on a production-grade Kubernetes cluster, our framework can help operators narrowing the focus only on informative data, and can proactively trigger actionable signals that anticipate Service-Level Agreements (SLAs) violations.

Altogether, we built a comprehensive suite of in-network monitoring tools and sketches to troubleshoot data center performance end-to-end.