My research aims to design network systems and propose optimization techniques for wireless networks. To this end, my research work falls into the following three categories:

1. Data analytics & design of deduplication middleware systems.
2. Functionality distribution in aggregation architectures.

I work ambitiously to bring cutting-edge research to mainstream practice. My research is based on a three step approach: (a) identify a unique engineering problem in the wireless context; (b) evaluate through simulation, emulation or implementation; (c) propose new modeling approaches and deployable systems or services. Heretofore, my ambition is for my ideas to flourish into a useful entity for the community. During this process, several practical issues may appear that require coordination among multiple organizational entities. My collaboration with IBM Research, Cisco, Samsung Research and NC State University, has helped me to evolve as an individual researcher and as a member of a group.

Data-driven Analysis & Design of Deduplication Systems

Data deduplication techniques can remove repetitive patterns in the traffic stream and decrease the response time for delay sensitive applications. The two most widely implemented object-level deduplication techniques are the browser and the proxy caches. For higher savings, Data Redundancy Elimination (DRE) techniques may be used. They identify redundancy at smaller granularity (packet-level, connection-level etc). However, it was not clear (a) how effective these techniques are in the mobile content, and (b) whether we can devise a new technique that can perform better. To answer these questions, we performed a trace driven analysis based on the following steps [7].

**Device Identification:** We have devised an Operating System (OS) Fingerprinting methodology that identifies each device type such as iOS, Android, BlackBerry, Windows, Mac OS X and Linux. The proposed technique is based on data mining principles and identified 98% of the devices in a wireless network (as compared to 84% for earlier approaches). The technique incorporated and validated the trustworthiness of several filters from different protocols (DHCP, TCP and HTTP).

**DHCP Traffic Analysis and Lease Time Policies:** We showed that DHCP message exchanges vary both across device types (e.g., laptops, smartphones) and across operating systems (e.g., iOS, Android, Windows, Mac OS X, Linux), with each device type contributing a different amount of DHCP related traffic and having a varying effect on the network address utilization. We proposed a new DHCP leasing strategy that does not require any protocol changes, and which takes advantage of the varying usage patterns per device type. Using simulation results, driven by traces, we showed that the new strategy, compared to current approaches, improves the network address utilization sixfold without considerably increasing the DHCP overhead.

**Web Traffic:** I examined Web traffic across both smartphones (iOS, Android, BlackBerry) and laptops (Windows, Mac OS X). We showed that smartphone browsers make less use of HTTP caching mechanisms, as compared to laptops. Multimedia content (audio and video) is a large fraction of traffic across all device types, and iOS users in particular consume a large amount of video in terms of bytes. Partial downloads occur frequently, and larger transfers are more likely to be aborted, particularly if the content is streaming video. Most video is retrieved using progressive downloads with range requests.

**Browser Caching:** We have investigated browser caching for each device type and showed that smartphone browser caches are not as effective as laptop caches. We have emulated a separate browser cache per device and showcased that adding a small browser cache to each device (10MB) is sufficient to capture most of the achievable savings. Browser cache savings vary widely across users, with benefits ranging from 0 to 80% in terms of both request hits and byte savings.

**Proxy Caching:** We have showed that a properly configured proxy cache may attain 8 – 40% of request hit rate and 5 – 25% of bandwidth savings. By breaking out the caching results per content type, we found that mobile video
content is not amenable so much to savings. In addition, the proxy cache must handle partial downloads, otherwise it can actually increase bandwidth consumption by a factor of 3.

**Data Redundancy Elimination:** Our analysis indicated that extra savings can be attained from web traffic, and 2 – 4% of extra savings can be gained from non-web protocols (e.g. Email, FTP etc.). Unfortunately, this advancement does not come without challenges: (a) Fingerprint generation is CPU intensive and can create a bottleneck in high-bandwidth WAN links; (b) Storing hashes per chunk in the memory may lead to a higher memory utilization compared to proxy caches; (c) Fingerprint generation, hash and chunk storage for some protocols may be useless.

**Hybrid DRE:** Motivated by these limitations, we designed an apparatus that combines the benefits and resolves the issues of the aforementioned data deduplication techniques. The proposed system is comprised of a scheduler, an object cache and a byte cache. The static scheduler forwards the cacheable content to the proxy cache, and the uncacheable content to the byte cache. We have also validated this system with actual wireless packet traces. The proposed implementation showed twice as much savings than a standalone proxy cache, and slightly better savings than a standalone RE system. However, compared to the standalone RE system, it requires three times less memory storage, and provides a speedup equal to three [3].

**Functionality Distribution in Aggregation Networks**
The second area of my research activity is on network design & dimensioning problems [4, 5]. This work has been motivated by the lack of established principles on the design of next generation aggregation architectures. More 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 is 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 set out to:

- Define the possible aggregation architectures: 1. *Centralized Single-Edge*, 2. *Centralized Multi-Edge*, and 3. *Distributed Single-Edge*. We further differentiate based on whether the edge system is clustered or maintains its functionalities in a single box.
- Develop 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.
- Propose 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, we have evaluated the model with two close-to-real-life scenarios and multiple traffic profiles, based on data provided by EU ISPs. Our results yield that ISPs will benefit from distributing the functionalities closer to the subscriber. Furthermore, sensitivity analysis suggests that ISPs should invest on systems that support more line cards and interfaces, rather devices with higher bandwidth.

**Performance Analysis of Wireless Networks**
The final area of my work deals with the analytical decomposition of wireless protocols. More specifically, I studied the Quality of Service (QoS) of 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 the current standards do not define principles for strict QoS [11, 16].

We used three common analytical approaches for wireless networks, namely Discrete Time Markov Chains, Closed form Queueing networks, and analysis using elementary conditional probabilities. We 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. We demonstrated that Block-ACKs may improve the QoS under erroneous channel conditions [8, 9]. We 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 [14]. 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 \cite{15}. 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 \cite{6}. During my collaboration with VTT Research Institute, I also applied the same analytical approaches on the energy consumption of WiMAX networks (IEEE 802.16e) \cite{13}.

**Summary & Future Work**

As you may notice from the above, my background combines principles from computer engineering and operations research, i.e. queueing theory, simulation, trace-driven analytics, data mining, and optimization. I particularly enjoy working on networking systems and designs that may improve the end user’s Quality of Experience. I strive so that my work has both a theoretical and a practical contribution, which is why I pursued a dual-degree PhD in Computer Engineering and Operations Research.

My perception is that shortly all services are going to be located in distributed areas (either virtual or geographical, c.f. cloud computing setting). These services will have to be delivered in resource-constrained smartphone devices that are mobile, and able to switch through multiple wireless interfaces. Hence, network systems will have to include the intelligence to hide the intrinsic complexity from operators and end users.

My plan is to extend some of my research ideas, and focus on transforming them into prototypes, and potentially into products. Finally, I will use my experience on invention disclosures and work towards building a portfolio of ideas in emerging fields such as cloud computing, mobile and storage architectures.

**References**


