Computer networks have become the fundamental infrastructure in modern computing systems, from providing Internet access to end users, to building large-scale distributed systems for cloud computing and data analysis. My research focuses on the development of networked systems that facilitate the management of physical and virtualized network resources for scalable, reliable, and efficient data delivery. Major application areas of my research include mobile and cloud computing as well as socio-aware and data-intensive applications. I am particularly interested in systems building and experimental evaluation in combination with analytical understanding. I use prototypes and simulations to experimentally evaluate the ideas in mind, and apply analytical modeling methods whenever possible.

My research brings together key ideas from the networking, computing systems, applications and data analytics communities. I actively collaborate with industry partners, including Cisco, NEC, Bell Labs, Volkswagen, Ericsson, ARM, China Telecom and Microsoft Research, as well as academic partners e.g., Columbia, Chicago, UCR, Cambridge, UCL, Uppsala, UPMC/LIP6 and Tsinghua, to discover challenging practical problems and realize research ideas via prototypes developed for real-world settings. These collaborations have led to research results in the form of publications in premiere venues, software and hardware prototypes, open-source software releases and patent applications. I will continue collaborations with them and actively seek new collaborations in the future.

Since getting tenured in early 2007, I have graduated 20 doctoral students in the areas of wired networking (5), mobile/wireless networking (4), cloud computing, software-defined networking and network function virtualization (5), security and privacy (2), social networks and data analytics (4), 10 out of which have become faculty members in USA, Germany, Ireland, India, Pakistan and China. I also supervised 8 additional postdocs/postgraduate fellows (including 2 Humboldt Scholars) who became faculty members in USA, Germany, Finland, and China. My current team comprises 2 postdocs, 9 PhD students as well as several master and bachelor students; we are continuously committed to high quality research with the aim of ensuring that our contributions remain relevant to the changing needs of the research community.

1 Current Research

Energy-Efficient Mobile Edge/Cloud Computing: With more and more computational tasks such as AR, VR or imagine processing desired by mobile users, rapidly developed mobile devices are still facing limited power and computational capability. To tackle this issue mobile edge/cloud computing paradigm has been proposed with the aim to offload the demanding computational tasks to remote cloud computing and recently edge computing devices, considering the energy efficiency and application requirements. We demonstrate that the time and energy consumption required for solving the offloading decision problem are substantial, which undermines the overall computational time saving envisioned by most previous studies [42]. We discover the indispensable need for online distributed offloading where multiple users are connected to the mobile edge infrastructure, and developed a novel game theoretic approach which tradeoffs energy consumption and user preference [9] and a device-to-device (D2D) assisted offloading approach [33]. This line of work reveals and exploits key real-life properties of computational offloading, and enables mobile cloud/edge computing to effectively apply for typical multiple simultaneous mobile users cases. Our work has received EU FP7 MobileCloud project funding.

Cloud Computing, Softwarized and Virtualized Resource Management: Online management of large-scale cloud and virtualized resources poses many challenges, which have attracted significant research. As emerging network appliances, such as firewalls, loadbalancing, QoS and DPI, are more and more implemented as software-defined virtual functions and converging on the cloudized and virtualized network infrastructure, the management of such functions becomes more and more critical. We develop a function-centric service chaining (FCSC) paradigm by introducing a function naming layer to the software-defined networking (SDN) architecture, which is shown to substantially reduce the flow table size and improve lookup performance [2] (best paper award); we further improve FCSC by developing DRENCH, a distributed resource management framework for NFV-based service function chaining [34]. We develop schemes for efficient placement of data and virtual machines (VMs) in clouds [38, 39]. We find the high communication costs with VM migration and develop LayerMover [41] and CBase [40] for live VM migration. More recently, we develop configuration and pricing schemes for cloud resources [31, 32], design NFVnice to schedule NFV resources cross-NFs and cross-CPU cores in a fair, efficient and dynamic manner [28], and further develop REINFORCE for resilience NFV services [27]. Topics on this line of research have been supported by EU FP7 CleanSky ITN under my coordination.

Socio-/Application-aware Data Delivery and Information-Centric Networking: My early works included the development of new protocols [13–16, 19, 36] to support efficient signaling for QoS resource reservation and middlebox configuration. According to Cisco VNI, busy hour (i.e., the busiest 60 minute period in a day) Internet traffic will increase by a factor of 4.8 between 2017 and 2022, exceeding the average Internet traffic increase of a factor of 3.7, thus the network dynamics like failures and demand spikes is gaining more importance. However, the Internet infrastructure was initially designed for deal with the large-scale network dynamics with statistical multiplexing and dynamic routing in a typically much longer period of time window. Although various efforts including more deployments of content distribution networks (CDNs) have been made, highly resilient and efficient content distribution has proven to be difficult. We found that existing schemes achieve only suboptimal performance in particular during spikes. We improved the efficiency for aggregated TCP flows [29], multipath data transfer [4, 5, 12], and explored how to leverage available bandwidth estimation for efficient develivery of delay-insensitive traffic [3]. We leveraged social relationships among users for scalable information delivery for microblogging-like systems [37]. We leveraged machine learning to detect behavior patterns of anomalies [17, 35]. We designed distributed socio-aware data placement and social networking platform to facilitate efficient data delivery [23–26]. We worked with teams within the EUJ GreenICN and ICN2020 projects to improve the efficiency of content and video delivery, disaster notification and connecting Internet of Things (IoT) nodes, by exploiting the information-centric networking paradigm [1, 6–8].

Social Networks and Big Data Analytics: Part of my work has been in close collaboration with colleagues from sociology, psychology, management, complex systems, earth/environmental and medical sciences, towards understanding the related actors' behaviors, interactions and evolution in various social systems, such as social media and other online platforms, human mobility, transport, corporate management, and healthcare. For example, we develop methods and tools for collecting related dataset [11, 18], study the identification and evolution of some social structures [10, 21, 43], behavior patterns of online shopping users [20,22], or quantifying the ego-centric network metrics [30].

2 Future Research

My future research plans revolve around the development of intelligent and scalable network infrastructure designs and applications. The extraordinary complexity of ICT development in society makes this a rich topic with many possible avenues of investigation. In particular, my agenda is not limited to developing more efficient and reliable protocols (although this certainly remains a challenge), but encompasses several other problems, including understanding of the interplay between system resources, service provisioning strategies and the dynamics of user demands and systems behavior, and applying my knowledge and experience to domains outside of computer networking, including computer vision, machine learning/data mining (ML/DM), health informatics, robotics, social and behavior sciences. I anticipate that the applications of this research will be numerous and diverse, for the simple reason that appropriate modelling of user and system behaviors has immediate relevance to anything that involves facilitating underlying computing and communication, as well as understanding and analyzing real-world events. Some specific potential research topics are briefly outlined below:

1. **Automated network service provisioning and management:** One strategy for tackling the service complexity issue is automated provisioning and management of such services. To deal with this, we plan to profile networks and network-based services, based on which devleop ML/DM-empowered algorithms and mechanisms to support online service placement and provisioning. Furthermore, the advent of micro-services in cloud computing brings additional challenges because it redefines the way in which the network functions interact and offer services. These new approaches demand revisiting existing works for network function placement and the development of new solutions that can exploit the benefits offered by micro-services. In light of this, I have recently submitted a new EU H2020 ETN research proposal to design techniques expoiting ML/DM to refactor network services and functions for automated network service provisioning and management.

2. **IoT for Connected Vehicules and Smart Cities:** Cities are getting smarter every day. ICT has been a key enabler for municipalities to optimize services for urban space and cities' (and citizens') wellbeings, which are paramount in planning cities of the future. The penetration and rapid growth of IoT would bring enormrous research oppportunities in the development of smart cities and their mobility options. For instance, the integration of heteregenous IoT data will allow new applications like data-driven planning (e.g., smart parking and car/bus-sharing, energy-efficient building), public safety/surveilance (e.g., crime/theft detection, social disorder), automous self-driving, and roadside/remote assistance. We are part of the recently started EU H2020 COSAFE project which investigates and develops innovative cooperative connected and intelligent vehicles (CIV) technologies and applications.

In the long run, the development of ICT infrastructure towards addressing various technological and societal problems will be a major part of my research work. In all my endeavors, I am excited to embrace new opportunities in the emerging research challenges, applying and expanding my experience to the very research front.

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