Performance Analysis in Wireless HetNets: Traffic, Energy, and Secrecy Considerations

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Abstract

To this day, most of the communication networks are characterized by a “monolithic” operating approach. Network elements are configured and operate without any reconfiguration for long time periods. Softwarization, whereby dedicated elements are being replaced by more general-purpose devices, has been lately challenging this existing approach. Virtualizing the infrastructure through the softwarization can provide significant benefits to end users and operators, supporting more flexible service deployment, providing real time monitoring and operational changes.

In this licentiate thesis, we consider techniques that can be used towards virtual networking. In Paper I we study a novel allocation technique and traffic optimization process for the access network. Cellular network technologies (i.e. UMTS, LTE, LTE-A) will coexist with non-cellular small cells and offload traffic from cellular to non-cellular networks mainly operating in 3GPP Wi-Fi (IEEE 802.11 standards). This is a scenario for indoor wireless access implementations where offloading mechanisms can improve the QoS offered by the operators, and reduce the traffic handled by the access fronthaul. The analysis of a novel optimization algorithm exhibited a holistic solution for access-core interworking where LWA (LTE-WiFi Aggregation) offers improved performance for the end users.

In order to optimize core network operations factors such as the operational costs should be addressed. Following this approach in Paper II we analysed how environmental factors (e.g. temperature, humidity) can affect the power consumption of core network data centers (cooling systems). By applying machine learning techniques using data from a data center, we were able to forecast the power consumption based on to atmospheric weather conditions and analyse its accuracy.

Optimizing the access network operations and the interworking (resource allocation, scheduling, offloading) can lead to highly configurable and secure operations. These have been factors of great concern as wireless connectivity increases in denser populated areas. In Paper III we examine the physical layer secrecy aspects of a collaborative small cell network in the presence of parallel connections and caching capabilities at the edge nodes. Using tools from the probability theory, we examined how the power allocation for the transmissions can ensure secrecy in the presence of an eavesdropper.

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Georgios Smpokos

Abbreviations

5G	Fifth Generation
AP	Access Point
API	Application Programming Interface
BS	Base Station
CAPEX	Capital Expenditure
CN	Core Network
CSI	Channel State Information
DC	Data Center
eMBB	enhanced Mobile Broadband
eNB	evolved node B
EP	Equilibrium Point
EPC	Enhanced Packet Core
HetNet	Heterogeneous Network
ICIC	Inter-Cell Interference Coordination
IoT	Internet of Things
LAN	Local Area Network
LTE	Long Term Evolution
LWA	LTE-WiFi Aggregation

MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mMTC	massive Machine Type Communications
MNO	Mobile Network Operator
MTC	Machine Type Communication
MVNO	Mobile Virtual Network Operator
NAS	Non Access Stratum
NF	Network Function
NFV	Network Function Virtualization
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PGW	Primary Gateway
PHY	Physical Layer
QoE	Quality of Experience
QoS	Quality of Service
RACH	Radio Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RTD	Round-trip Delay
SDN	Software Defined Networking
SGW	Secondary Gateway
SIA	Service to Interference Assignment
TOTFA	Traffic Offloading and Transmission Time Fraction Allocation

UE	User Equipment
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNF	Virtual Network Function
VPN	Virtual Private Network
VR	Virtual Resource
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WVN	Wireless Virtualized Network
WSP	Wireless Service Provider

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Part I

Introduction

1 Network Virtualization

In recent years there has been an increasing demand for high throughput, low latency, energy efficiency, security and connectivity prompted by massive numbers of connected multipurpose devices, Internet of Things (IoT). The ongoing explosion in connectivity requirements and the increasing demand for real-time services e.g., video streaming and live conferencing, are stretching the already limited capacity of the deployed network systems and operations. All these requirements have paved the way to a new era for communication standards and deployments, leading to the Fifth Generation (5G) of networks, affecting both research and standardization [1-3].

New Physical Layer (PHY) methods for the 5G standards have already been proposed and tested including Multiple-Input Multiple-Output (MIMO) systems, full duplex scenarios, and modulation schemes. Novel physical layer technologies such as Inter-Cell Interference Coordination (ICIC), will lead to an increased spectrum efficiency as more Heterogeneous Network (HetNet) implementations will offer the required services to the subscribers [4, 5]. HetNets used for optimizing user experience and reducing the cellular network traffic have been examined and will eventually lead to more efficient resource allocation for multiple services utilizing a variety of access technologies [5-8].

Currently, the dedicated hardware-based core and access network components cannot provide the necessary flexibility and efficiency at the control plane (switches, gateways, controllers). Due to these factors, a new backhaul network core-access architecture has to be adopted based on Software Defined Networking (SDN) and Network Function Virtualization (NFV) paradigms [9-12].

1.1 Resource Allocation and Scheduling

As we are entering the IoT interconnected era, next generation networks need to support heterogeneous services with diverse specifications. These specifications should lead to a network operation where resources, both physical and virtual, are being efficiently allocated and scheduled to the users. In [16] the authors have tried to optimize the mechanism of allocating Virtual Resources (VR's) based on multiple application demands at the user end, introducing two different algorithms for resource allocation. The users could be served by

more than one interface (Radio Access Network (RAN) technology) such as Long Term Evolution (LTE), IEEE 802.11.x (Wireless Fidelity (WiFi)). The purpose of the optimization was to minimize the total utilization cost of each interface's resources based on user demands namely the Service to Interference Assignment (SIA) problem. Additionally, the authors of [17] suggested a novel optimization of resource allocation approach using Linear Programming and the Lagrangian duality theory. The results demonstrated great advantages when adopting a flexible allocation strategy in time and frequency domains, eventually increasing the utilization of network capacity for mission critical services. Based on the concept of LTE-WiFi Aggregation (LWA), the authors of [18] studied an LWA-enabled network that included an LTE Base Station (BS) and a Wi-Fi Access Point (AP) where a non-ideal backhaul affected the LWA design parameters such as throughput and delay performance.

Backhaul capacity improvements and denser deployments of HetNet's will eventually increase resource availability and enhance the end to end Quality of Service (QoS). Motivated by this, the authors of [19] presented a scheduling mechanism within a two-tier HetNet deployment, where traffic offloaded to femto-cell BS's is served by the core network via residential broadband connections. In this constrained backhaul capacity scenario, the implementation of Traffic Offloading and Transmission Time Fraction Allocation (TOTFA) was examined while proportional fairness regarding throughput among users was applied.

Fairness among users for resource allocation is an important concept that can be applied for high density and multi-purpose multi-service network implementations. Fair traffic allocation and aggregation in HetNet's is of a great significance as more network operators utilize low power Wireless Local Area Network (WLAN) femto-cells where traffic is offloaded from LTE or other next generation macro cell Radio Access Technologies (RAT's). Following these, in [20] the authors have proposed an algorithmic solution for splitting traffic in LTE-WLAN HetNet's based on LWA while experiencing some network backhaul delay and maximizing the average User Equipment (UE) throughput performance. By implementing a water filling technique for allocating macro cell resources, the proposed mechanism performs better than other RAT selection algorithms that had been proposed and implemented. This work has been the foundation of our study in Paper I where the concept of slicing (grouping the end

users) could lead to an improved resource scheduling mechanism.

A market oriented problem of allocating VR's where Mobile Network Operators (MNO's) offer their VR's to Wireless Service Providers (WSP's) while maximizing the utilization within a Wireless Virtualized Network (WVN) is studied in [21]. The authors of this work proposed an analytical solution for allocating Orthogonal Frequency Division Multiple Access (OFDMA) orthogonal subcarriers (spectrum allocation), eventually reaching an Equilibrium Point (EP) where both the MNO and the WSP maximize their profits. This maximization of the utilization of the available VR's takes into consideration the quality of the channel (Channel State Information (CSI)) extracted from the subscribers. The algorithm used to solve the problem converges, performing a per resource price adjustment based on the supply and demand values of VR's.

1.2 Software Defined Networking

Following the paradigm of Data Centers (DC's) and Local Area Networks (LAN's) where virtualization (Virtual Local Area Network (VLAN), Virtual Private Network (VPN)) has been widely deployed, both the network elements and services will be transformed to virtual commodities. This transformation will reduce the operation and deployment costs, centralize the control, and become more susceptible to future upgrades. SDN technologies aim to drive this implementation of virtual networks, more specifically by decoupling network control from the forwarding functions, thus decoupling control and data planes [10, 22].

In [9] the authors explicitly analysed the key features that 5G technologies and networks should support, such as increased traffic volumes, high user data rates, low latency and supporting a high number of Machine Type Communication (MTC) devices in the IoT framework. The need for power efficiency at the user end was considered as well as how the reduced operation costs could benefit a Mobile Virtual Network Operator (MVNO) operating a virtual network. Notably, the proposed architecture introduces the notions of SDN and NFV simultaneously to the RAN and Core Network (CN) making the entire network highly programmable, scalable, and ready for the virtualization of its components.

Bottlenecks for applying virtualization at the CN have been extensively studied in [15]. In this work the authors studied the perfor-

mance of Enhanced Packet Core (EPC) components of the backhaul network being operated in a virtual environment. Furthermore, this research focused on defining the impact of control plane misbehaviour in user plane data flow performance. The model used for this research was based on real life traffic data provided by an MNO. The number of control plane events were critical in managing and processing the traffic of the data plane. After the detailed analysis of Non Access Stratum (NAS) events, the authors concluded that the Secondary Gateway (SGW) is crucial in terms of control plane signalling but also in data-user plane traffic flow and thus should be taken into consideration when transforming the hardware into virtual functions. In [23], the Virtual Network Function (VNF) placement and its implementation was extended to the RAN and a novel VNF placement algorithm was studied. In this problem's definition the authors took into consideration forwarding and processing characteristics of the network nodes as well as the capacity of the virtual interconnection links. The proposed VNF placement heuristic could eventually allow MVNO's that do not own any physical CN or RAN resources to implement resource allocation for service provisioning and delivery.

HetNet Cloud infrastructure as part of an SDN framework of HetNets has been extensively examined in [24] where the authors emulated a scenario using Mininet simulations tool. In that work the research was focused on a detailed overview of an end-to-end virtualized infrastructure where control plane entities reside in servers decoupled from any hardware middleboxes. Southbound and Northbound Application Programming Interfaces (API's) were presented and QoS constraints such as Round-trip Delay (RTD) affecting services such as live voice and video sharing have been examined. That work identified that topology for the placement of Virtual Machines (VM's) on the physical substrate must be very carefully examined and planned in any HetNet SDN implementation. In [11] the authors applied NFV and offloading to Multi-access Edge Computing (MEC) servers in order to study the end-to-end service performance of a communication system. Through that analysis they derived approximate analytical expressions for the end-to-end delay, throughput, and drop rate.

2 Optimization of Core-Access Networks

The technologies covered in the previous section enable flexibility through the softwarization of the network components as well through separating the control and data planes (network subsystems control and user plane for data transmission) eventually offering upgradability, optimization, and customization of networking [4]. For a network that will host users with very different and versatile needs and requirements in terms of throughput, latency, availability, and security, the MNO's and MVNO's need to classify their subscribers into user groups. This separation will be based on user requirements and will assist in providing advanced services through the creation of virtual network slices, reducing the signalling, control overhead, and optimizing the coordination of core with RAN interfaces and components [13, 14].

The centralized management controllers of the network will coordinate physical and virtualized processes such as routing, spectrum allocation, power efficiency, and caching, to name a few. These managements tasks need to be further investigated while novel optimization algorithms should be introduced to cope with the excess of data traffic in various HetNet implementations [9]. In order to achieve the aforementioned goals, the bottlenecks of virtualizing the core and access network functionality needs to be evaluated and thoroughly examined [15].

2.1 Network Slicing

In the context of offering multiple services with diverse specifications (video, voice, real-time and reliable communications) and to multi-purpose devices (IoT, automotive, smartphones), network operators should define and implement end to end slicing. Slicing the network will offer isolation, functional, and performance independency and security in both core and access levels [13, 14, 22, 23].

In [13], a flexible architecture implementing network slicing demonstrated how different functions could be controlled and be set effectively for end to end services. The authors pointed out the importance of having a flexible realization of end to end slices and proposed a selection-attachment mechanism for users to further reduce control signalling. That scenario included two different network slices dedicated to two user groups namely enhanced Mobile Broadband (eMBB)

and massive Machine Type Communications (mMTC) users [26]. It was emphasized that some of the core Network Functions (NF's) can be migrated to the access-RAN domain as this will reduce the signalling traffic and increase the Quality of Experience (QoE) offered to the end to end slice members. By applying slice registration requests and selection at the access network entities, operators could achieve less attachment delays enabling faster slice access by introducing a dedicated Radio Access Channel (RACH) slice.

In [14] a holistic mobile packet core network implementation on SDN and NFV was proposed namely the V-Core. This approach introduced an SDN controller that could define the slicing and services provisioned per user plus separate the CN into different control planes operated by different MVNO's. After analysing the network topology for V-Core the authors illustrated the layered (control, data) structure of data flows indicating that not only the control plane could reside on cloud-virtual infrastructure. Additionally, the data plane functions (SGW and Primary Gateway (PGW) for LTE networks) could be implemented in a similar fashion. That study has finally indicated the cost efficiency of this implementation by significantly reducing Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) compared to old fashioned hardware based network implementations.

2.2 Energy Efficiency

In order for the network operators to reduce their OPEX, energy consumption and efficiency could become one of these elements to be optimized. Both in access and core networks energy consumption has greatly affected the operational costs while driving high power amplifiers at the edge of cellular networks or hosting core elements and servers in DC's [27-30]. As caching will be deployed at the edge of the networks and not solely at the CN, energy efficiency can be highlighted as one of the main elements to be optimized regarding the operations. Especially within DC's, a big portion of the power consumption comes from the cooling systems operated to control the temperature levels within them [31].

Patterns of energy consumption can be traced and identified similarly to traffic patterns indicating higher demand at specific periods of time. Making the energy consumption of multiple network elements more efficient will enable a greener operation of the network. Predict-

ing the energy consumption could eventually lead to a better usage of energy generated by renewable resources. Identifying these patterns can be realized using data from the operation and some preliminary data analysis. Moving further, predictions on the consumption can be performed using machine learning techniques where models can be used to forecast energy requirements e.g. in DC's their energy consumption [32–35].

2.3 Security and Caching

Another significant factor affecting the overall operations of the MNO's has been the security of their networks. Although fiber optics had offered a secure transmission down to the last mile of edge networks, the physical layer (PHY) security of wireless access networks needs to be further examined and studied. Studies have proved that secure physical layer wireless communications can be established over noisy channels and fading conditions and enable secrecy and reliability for the connectivity [36–45].

In order for small cells to establish and utilize in terms of stability and security multiple connections, caching needs to be available at the edge nodes [46, 47]. Caching popular content at specific nodes could also assist in reducing latency and processing within the network. This can be achieved evolving the RAN data plane where 5G evolved node B (eNB)-base stations will be able to split the protocol and hardware functionality, will be programmable to support multiple RAT's and support caching at the edge.

Caching could eventually improve the stability of networks by providing the most popular content to users that are served in a specific area by storing it in edge caches [48, 51]. Storing content at the edge nodes can offload a significant amount of traffic from CN's, improve the stability of the overall network and offer high QoE to the end users. Specific caching scenarios with different KPI's have been examined and optimized, such as the cache hit ratio, the cache-aided throughput [52], and the energy efficiency [53]. In [54] a cooperation setup has been proposed that minimizes the average energy consumption of a UE in order to receive its requested content. The QoE for edge users is studied in [55] where a novel algorithm is proved to optimize the user QoE and increase network performance by applying Machine Learning (ML) techniques.

3 Publications and Contributions

The respective research items, dealing with i) an optimal algorithm implementation for resource allocation in heterogeneous access network, ii) the energy consumption forecasting based on machine learning techniques, and iii) physical layer secrecy for access networks with caching capabilities are presented in the following sections.

The main contributions are summarized as follows:

- Optimal resource allocation algorithm implementation for the access network for reducing users' average delay performance.
- Allocating resources to slices of users satisfying throughput and delay requirements.
- Data analysis and correlation of energy consumption in core data centers with external weather conditions using machine learning techniques.
- Identifying the effects of caching on the performance of a system under different traffic characteristics.
- The analysis of the impact of physical layer secrecy on the delay and throughput performance of heterogeneous networks.

The research papers are summarized below:

Paper I: Performance Aware Resource Allocation and Traffic Aggregation for User Slices in Wireless HetNets, co-authored with Athanasios Lioumpas, Theodoros Mouroutis, Yiannis Stylianou, and Vangelis Angelakis. The paper has been published in *Proc. of IEEE 22nd International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD)*, June 2017.

In Paper I, the performance of an optimal resource allocation algorithm is examined while adding a new delay aware process aiming in jointly achieving predefined throughput and delay performance for selected groups/slices of users. From the optimal resource allocation, an algorithmic solution was derived which can be applied to determine an optimal number of network slices to be served. Determining

how to jointly assign spectrum resources and power for these optimization problems by using discrete rate levels and discrete power levels is investigated.

Paper II: On the Energy Consumption Forecasting of Data Centers Based on Weather Conditions: Remote Sensing and Machine Learning Approach, co-authored with Mahamed Elshatashat, Athanasios Lioumpas, and Ilias Iliopoulos. The paper has been published in *Proc. of IEEE 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, September 2018.

Paper II exploits the data provided by the FIESTA-IoT platform [56] in order to investigate the correlation between the weather conditions and the energy consumption in a data center. Using multi-variable linear regression, correlation between the energy consumption and the dominant weather condition parameters is modelled in order to effectively forecast the energy consumption based on the weather forecast. The machine learning technique used in this research utilised a backward elimination mechanism to extract the most significant independent parameters affecting the power consumption.

Paper III: Performance Analysis of a Cache-Aided Wireless Heterogeneous Network with Secrecy Constraints, co-authored with Zheng Chen, Parthajit Mohapatra, and Nikolaos Pappas. The paper has been submitted in *IEEE Access*, January 2021.

Paper III deals with the investigation and analysis of the performance of a wireless system with caching capabilities while imposing secrecy constraints at one of the users being served. In this paper the system model where an eavesdropper is introduced and the caching characteristics were deployed and defined. Next, the analysis based on queuing theory was introduced and the closed forms for throughput and delay performance were extracted. Two distinct demodulation schemes were analysed and results were produced for the comparison. The effects of caching on the secrecy of the system was examined and two demodulation schemes were compared. Finally, two optimization problems were set in order to get optimal setting values for this scenario and achieve maximum throughput and minimum delay values for each user.

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Part II

Papers

Papers

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