Chapter

Softwarization in Future Mobile Networks and Energy Efficient Networks

Thembelihle Dlamini

Abstract

The data growth generated by pervasive mobile devices and the Internet of Things at the network edge (i.e., closer to mobile users), couple with the demand for ultra-low latency, requires high computation resources which are not available at the end-user device. This demands a new network design paradigm in order to handle user demands. As a remedy, a new MN network design paradigm has emerged, called *Mobile Edge Computing* (MEC), to enable low-latency and location-aware data processing at the network edge. MEC is based on network function virtualization (NFV) technology, where mobile network functions (NFs) that formerly existed in the evolved packet core (EPC) are moved to the access network [i.e., they are deployed on local cloud platforms in proximity to the base stations (BSs)]. In order to reap the full benefits of the virtualized infrastructure, the NFV technology shall be combined with intelligent mechanisms for handling network resources. Despite the potential benefits presented by MEC, energy consumption is a challenge due to the foreseen dense deployment of BSs empowered with computation capabilities. In the effort to build greener 5G mobile network (MN), we advocate the integration of energy harvesting (EH) into future edge systems.

Keywords: softwarization, energy harvesting, soft-scaling, energy self-sustainability, forecasting

1. Introduction

The evolution towards a softwarized evolved packet core (EPC) is the driving force towards overcoming the challenges observed in current mobile networks (MNs) and set the way for handling the high data rate and ultra-low latency demands required by mobile users. This change avails the possibility of running network functions (NFs) in software, instead of proprietary hardware devices, and also it permits the possibility of dynamically scaling the network resources for a more robust network management in 5G and beyond as network complexity is reduced. Softwarization and virtualization of resources and services are undoubtedly among the main drivers of 5G and beyond 5G networks, as they will provide the mechanism for network management, that is, network flexibility and adaptability is guaranteed [1, 2], and also facilitate network maintenance and update all networks with ease.

To address the need for MN evolution, different design approaches have been investigated towards the state-of-the-art EPC architecture where vendors and researchers proposed the (i) grouping of the EPC functions [3–5], (ii) running the virtualized functions on clouds [6, 7], (iii) partitioning the network resources into network slices [8–11], which refers to an isolated set of (programmable) resources to enable NFs and services, and (iv) redesigning the network to be based on network function virtualization (NFV) technology [12, 13].

The architectural evolution involving the redesigning of the network based on NFV is currently appealing towards 5G and beyond, as it allows the virtualization of the mobile NFs and then placing them within the access network. This is motivated by the expected data explosion in the volume, variety, and velocity, generated by pervasive mobile devices and the Internet of Things [14] at the network edge (i.e., in close proximity to mobile devices, sensors, actuators, and connected things). This is coupled with the demand for stringent latency, requiring high computation resources which are not available at the end-user device. As a remedy, *Mobile Edge Computing* (MEC) has recently emerged to enable ultra-low latency, distributed intelligence and location-aware data processing closer to mobile users [2, 12, 13]. Undoubtedly, offloading to a powerful computation resource-enriched MEC server located closer to mobile users is an ideal solution.

Software-defined networking (SDN) and NFV are the emerging virtualization technologies that will enable flexibility and agility in MNs. SDN supports programmable interfaces to provide flexibility and agility on the network control management [14, 15], and NFV softwarizes the mobile NFs [16]. Both technologies limit the use of specialized hardware devices as they have been the limiting factor towards MNs evolution and the fast deployment of new services within the mobile space. The technologies can co-exist within the same network, where SDN employs a centralized approach on switching and routing elements [3], while NFV migrates the NFs out of dedicated hardware into software that is imported into general purpose hardware. In addition, these technologies are expected to facilitate the ease of efficient network management. The key to virtualization is that it enables *on-demand* or *utility* computing, a just in time resource provisioning model in which computing resources such as central processing unit (CPU), memory, and disk space are made available to applications only as needed and not allocated statistically based on the peak workload demand [17].

In light of the dense deployment pattern that is foreseen in 5G systems [18], the expected dense deployment of MEC servers and base stations (BSs) raises concerns related to energy consumption. Specifically, energy drained in BSs is due to the always-on approach (dimensioned for maximum expected capacity, yet traffic varies during the day), and in MEC servers, it is due to the computing-plus-communication processes associated with: (i) the running virtual entities [virtual machines (VMs) or containers] [19, 20]; (ii) the communication within the server's virtual local area network (VLAN) [21], and the presence of transmission (optical) drivers (fast tunable optical drivers for data transfer) within the MN infrastructure [22, 23]. Since energy consumption is a challenge within a BS system and the virtualized computing nodes (i.e., MEC servers), quantifying the energy consumption within computing platforms and transmission nodes is of great importance towards the development of robust energy management procedures. In addition, to address the carbon footprint emission and dependence in the powered grid, methods for using renewable (green) energy coupled with sustainable energy storage solutions are now receiving more attention than before. The motivation towards green energy is that the components in solar- and wind-based systems are usually modular, which makes the design, expansion, and installation of these types of systems for the BS sites very practical and feasible. This result in energy harvesting (EH)-powered BSs (EH BSs) and MEC (EH-MEC) systems.

1.1 Softwarization of mobile networks

Softwarization and virtualization is the driving force towards network evolution. Towards this end, researchers from industry and academia have presented different proposals towards the EPC architectural evolution. Their contributions result into fragmented inputs (see [2] for more details about EPC architectural proposals), with a unified goal of having an energy efficient EPC architecture for future MNs. The outcome is designs/proposals that are somehow overlapping in terms of the functions being softwarized, technologies used, and so forth.

1.1.1 Virtualization technologies and tools

The virtualization tools consist of the *hypervisor* and *docker engine*, and they are illustrated in **Figure 1**. Virtualization making use of the hypervisor is referred to as *hypervisor-based* virtualization, with the VMs as the computing resources or computer emulators, and for the environment using docker engine is referred to as *container-based* virtualization, with the containers as the computing resources. These different virtualization techniques share a similar architectural structure. However, the way in which each technique builds virtualized applications on top of the underlying supporting software is rather different.

A *hypervisor-based virtualization* simply isolates the operating system (OS) and applications from the underlying computer hardware [24]. This abstraction allows the underlying "host machine" hardware to independently operate one or more VMs as "guest machines" (also referred to as guest VMs), allowing them to share the systems physical computing resources, such as processing time, memory space, network bandwidth, etc. The hypervisor is the software that provides the environment in which the VMs operate. A new agnostic OS is generated to manage the underlying resources. Since the hypervisor sit between the actual physical hardware and the guest OS, it is also referred to as virtual machine monitor (VMM).

Container-based virtualization involves the use of containers as the computing resources within the virtualized computing platforms. Containers are abstraction units for isolating applications and their dependencies that can run in any environment. They can run on the same machine, on top of the docker engine, sharing the OS kernel with other containers. The docker engine is a software technology written

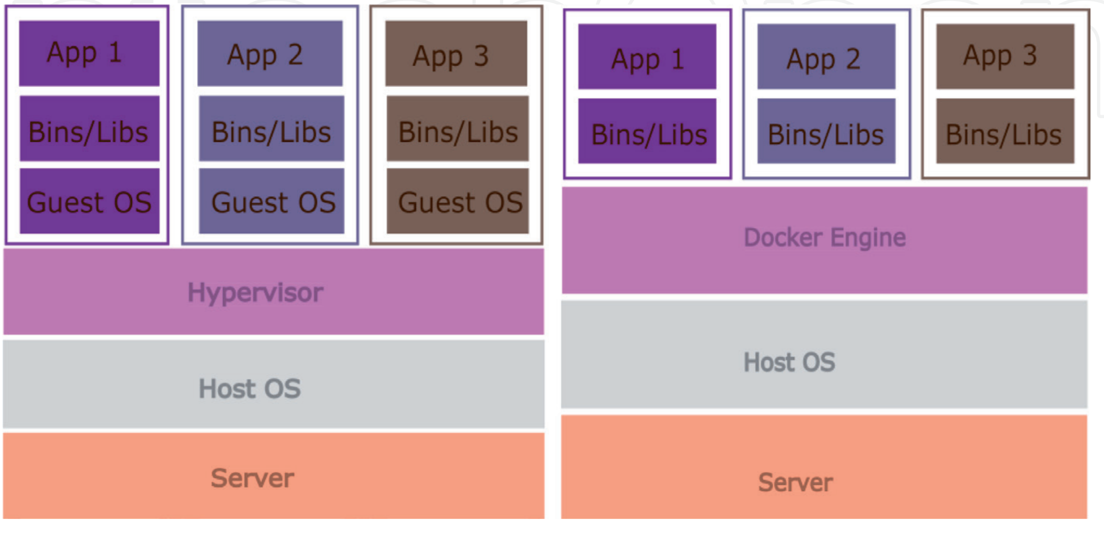

Figure 1.
An illustration showing the architectures of virtualization technologies: hypervisor-based virtualization (left) and container-based virtualization (right) [2].

in the Go programming language and it avails the environment for developing and running applications. It runs natively on Linux systems (in recent Linux kernels), where it uses Linux kernel features like namespaces, to provide a private, restricted view on certain system resources within a container (i.e., a form of sandboxing), and control groups (cgroups), a technology that limits an application to a specific set of resources (i.e., provides resource management, e.g., limits and priorities, for groups of processes). We observe that the entire OS level architecture is being shared across them. The only parts that are created from scratch are the *Bins* and *Libs*. Despite the process isolation and lightweight character, containers are less secure and more vulnerable compared to hypervisor-based virtualization, and thus, they can be used as alternatives of hypervisor-based virtualization.

Determining the most suitable technology for a specific scenario requires a thorough analysis of the scenario design and performance requirements, along with an ultra-careful analysis of the benefits and drawbacks associated with the use of one tool over the other. What can be observed is that virtualization tools can play a role towards energy efficiency (EE) improvement within MNs. Considering the hypervisor-based virtualization, the hypervisor can report resource usage to the orchestrator in order to trigger system automated sleep mode states and also to implement policies that are provided by management and orchestration entity, which includes power management and power stepping [24]. On the other hand, container-based virtualization can be considered as an alternative of hypervisor-based virtualization, as containers demand less memory space, portable and lightweight, and have a shorter start-up time which translates to low latency and power consumption [19].

1.1.2 NFV-based EPC architectural evolution

The works of [6, 7] proposed the use of a cloud-based approach with NFV platform, for the EPC evolution, in order to enable dynamic deployment of edge networks, the scaling of NFs, network monitoring, and load management. Both architectures avail the possibility of intelligently pooling capacity of resources when required.

In [6], the key elements of the architecture are (1) data-driven network intelligence for optimizing network resources usage and planning and (2) relaying and nesting techniques: to support multiple devices, group mobility, and nomadic hotspots. The EPC is virtualized into three parts, namely: (i) control plane entity (CPE), which is responsible for authentication, mobility management, radio resource control, and non-access stratum (NAS) and access stratum (AS) integration, (ii) the user plane entity (UPE), acting as a gateway, mobility anchor, and over-the-air (OTA) security provisioner. Lastly, (iii) the network intelligence (NI) plane is for the extraction of actionable insights from big data, orchestration or required services and functionalities (e.g., traffic optimization, caching, etc.). The realization of the network cloud can be achieved by enabling virtual function instances to be hosted in data centers when needed. The use of virtualization techniques will enable quick deployment and scalability of CPE and UPE functions. For example, in case of a natural disaster, with this technology, the local data center maybe unable to cope with the traffic upsurge; therefore, additional capacity can be sourced quickly from other data centers. A different strategy is employed in [7]. In that paper, the EPC architectural proposal simply abstracts the EPC network functions, decomposing and allowing them to run as software instances (virtual machines), on standard servers. This allows service providers to customize services and policies to design networks in new ways, to reduce costs, and simplify operations.

The aforementioned architecture proposals differ from one another. SDN is integrated with NFV in [6] to provide network control and to host the network intelligence, and in [7] only the NFV platform is available for enabling network services provision. Moreover, the architecture proposed in [7] is commercially available. Their contributions towards energy efficiency is as follows: (i) both make use of NFV and cloud computing platforms, and this avails the possibility of dynamically scaling resources based on demand as presented in [6] and (ii) through the information centric approach (collection of user-centric, network-centric, and context-centric data), intelligent algorithms, mainly network optimization tools, can be applied to the aggregated data in order to provide useful outlook for network planning and resource management.

2. Energy efficient in future mobile networks

There is growing awareness to the fact that the communication sector uses significant amount of energy [25]. This is especially true for wireless and in particular for the BSs of cellular networks, where energy costs make up a large part of the operating expenses of mobile operators. In addition, in future MNs, the BSs will be empowered with computation capabilities to enable local workload offloading (computation) and the provision of ultra-low latency services, as well as EH systems. This gives rise to the need for efficient energy management procedures employing machine learning and control-theoretic techniques, within the MEC paradigm.

2.1 Network infrastructure

As EH technologies advance, powering the network apparatuses (edge systems) with green energy (e.g., solar and/or wind) is a promising solution to reduce on-grid power due to their location, reliability, carbon footprint, and cost. The network infrastructure is illustrated in **Figure 2**, where a computing site is shown. The virtualized computing platform (MEC server) consists of the VMs (this can also be

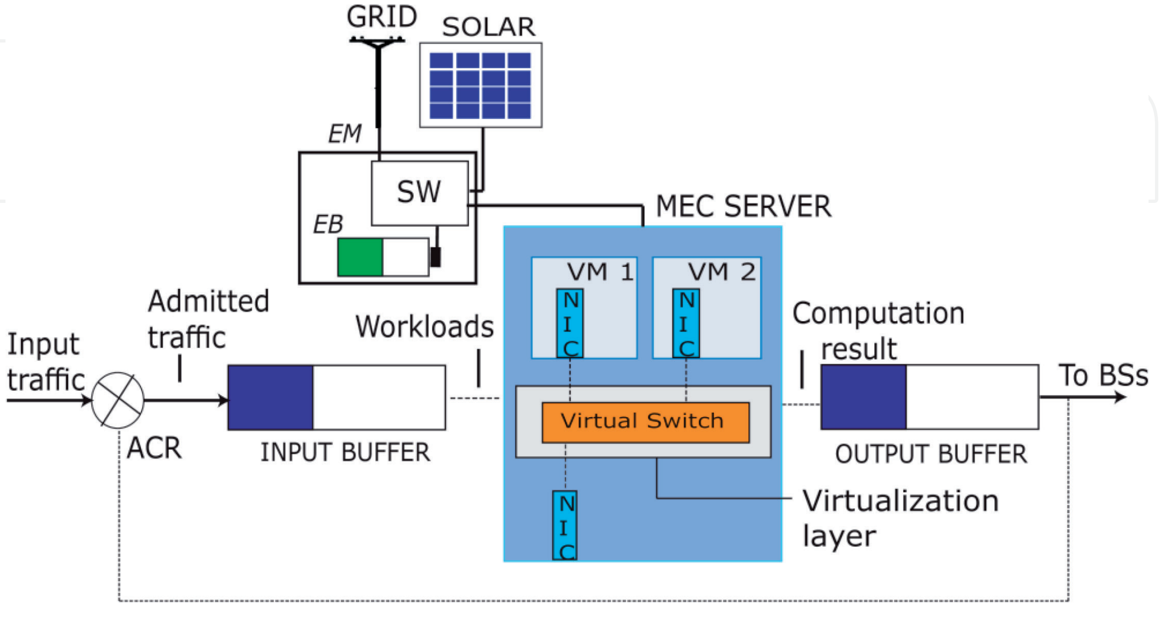

Figure 2.
The virtualized network infrastructure powered by hybrid energy sources: On-grid power and green energy. The electro-mechanical switch (SW) selects the appropriate source of energy [26].

containers), as the computing resources, empowered with EH capabilities through a solar panel and an energy buffer (EB) that enables energy storage. The power grid is also available for energy back up. The MEC node is assumed to be equipped with higher computational and storage resources compared to the end-user device. The energy manager (EM) is an entity responsible for selecting the appropriate energy source and for monitoring the energy level of the EB. The virtualized access control router (ACR) acts as an access gateway, responsible for routing, and it is locally hosted as an application. The input and output buffer are responsible for buffering admitted computation workload and storing aggregate computation results.

2.1.1 Energy consumption

As suggested by ETSI [12, 27], the virtualized network functions (VNFs) can be deployed at the base station (BS), that is, the BS site is empowered with computation capabilities where the MEC server is co-located with the BS or placed at an aggregation point (a point in close proximity to a group of BS) for edge network management.

We consider a MEC deployment scenario where the BS is co-located with a MEC server, as an example, and the total energy consumption ([J]) for the communication site is formulated as follows, inspired by [28, 29] and the virtualization knowledge from [21]:

$$\theta_{Tot}(t) = \theta_{BS}(t) + \theta_{MEC}(t),$$

where $\theta_{BS}(t)$ is the BS transmission energy (the load independent and the load dependent component), $\theta_{MEC}(t)$ is the energy drained due to computation and due to intra-communications processes in the MEC server at time slot t. It is worth noting that the computational (MEC) energy cost includes: (i) the energy drained due to the running computing resources (VMs or containers), w.r.t CPU utilization, (ii) the energy drained due to VM/containers switching their processing rates, and (iii) the energy induced by the transmission control protocol (TCP)/Internet protocol (IP) offload on the network interface card (NIC, partial computation at the network adapter such as TCP/IP checksum offload). Regarding the communication energy cost, we have energy drained due to the communication links (to-and-from each VM/container) and the energy drained due to the number of transmission (optical) drivers used for the data transfer to target BS(s).

2.2 Energy saving strategies in MEC

Considering the ultra-dense deployment of BSs and the dynamic characteristics of MNs, energy saving is of importance in green networks in order to exploit the benefits of sustainable computing and networking within edge systems. The sources of energy consumption in MEC are the BSs and the computing platforms. Towards this end, two large trends appear in the literature to address the energy efficiency challenge: (i) search for more energy efficient transmission devices and technologies; (ii) new technology proposals aimed at improving energy consumption in BSs, such as sleep mode, as it is known that switching on/off the BS transmission power during low traffic demand can yield significant energy savings [30–32]. Trend (ii) is more appealing due to the fact that future BS functions will be virtualized [1], thus enabling the ease of deactivating some of the BS functions. Within MEC servers, a joint *soft-scaling* (the reduction of computing resources per time instance) of the computing resources and the provision of minimum number of transmission drivers for data transfer to BS(s) in real-time is appealing.

2.2.1 Sleep-modes strategies in MNs

The dramatic growth in mobile data has spurred the dense deployment of small cell BSs to enhance spectrum efficiency and increase network capacity. Although small cell BSs consume less power compared with macro BSs, the overall power consumption of a large number of small cell BSs is phenomenal. To address the energy saving procedures, sleep mode is adopted. The sleep mode application can be observed from a single mobile operator or multiple operators perspective, with the main goal of maximizing energy savings without any significant network impact.

Towards energy savings in dense environment clustering algorithms have been proposed as a way of switching off BSs to reduce the energy consumption within MNs [33, 34]. However, the dynamic BS switching on/off strategies may have an *impact* on the network due to the traffic load that is offloaded to the neighboring BSs. To avoid this, the BS to be switched off must be carefully identified within a BS cluster. In [35], the *network impact* is used to identify the BS to be switched off within a cluster, one at a time, with no significant network performance degradation. Moreover, the network impact has been used in [36] to identify a BS to be switched off within a BS cluster where each BS is empowered with computation capabilities. With the advent of EH, it is desirable to incorporate the green energy utilization as a *performance metric* in traffic load balancing strategies [37, 38].

In the effort of greening future MNs, BSs are expected to be powered by green energy sources. On the other hand, NFV technology is expected to improve energy consumption by enabling the BS sleep modes, that is, scaling down the NFs during low traffic periods [24] or at low EB levels. Along the lines of MN softwarization, a distributed user association scheme that makes use of the soft-radio access network (RAN) concept for traffic load balancing via the RAN controller (RANC) is presented in [37]. Here, the user association algorithm is proposed and it runs in the RANC. The role of the algorithm is to enhance the network performance by reducing the average traffic delivery latency in BSs as well as to reduce the on-grid power consumption by optimizing the green energy usage. In cases where there is no centralized entity for edge network management, the need for distributed algorithm arises, which is the case with BSs co-located with MEC servers.

Furthermore, towards the effort of reducing the energy consumption through BS sleep modes, it is observed in the literature that most of the existing works considered clusters of BSs from a single mobile operator perspective, where some functions of the BS can be switched off and then the remaining active BSs handle the upcoming traffic. A new mechanism is presented in [39], which exploits the coexistence of multiple BSs from different mobile operators in the same area. An intra-cell roaming-based infrastructure-sharing strategy is proposed, followed by a distributed game-theoretic switching-off scheme that takes into account the conflicts and interaction among the different operators. Then, the work [40] of investigate the energy and cost efficiency of multiple HetNets [i.e., each HetNet is composed of eNodeBs (eNBs) and small cell BSs from one operator] that share their infrastructure and also are able to switch off part of it. Here, a form of roaming-based sharing is also adopted, whereby the operator can roam its traffic to a rival operator during a predefined period of time and area. An energy efficient optimization problem is formulated and solved using a cooperative greedy heuristic algorithm.

2.2.2 Energy savings in virtualized platforms using soft-scaling

To address 5G use cases in a more energy efficient way, visibility into power usage is required for developing power management policies in virtualized computing platforms (i.e., MEC servers or data centers). In virtualized computing platforms, the energy consumption is related to the computing and communication processes. To minimize energy consumption within such environments, energy saving studies have involved the scaling up/down of servers/VMs [29, 41–43], VM migration (process of duplicating and transmitting the VM memory image over the network, in virtualized data centers, without or least service interruption [44]), and soft resource scaling (shortening the access time to physical resources [45]). With the advent of NFV, it is expected that the NFV framework [24, 46] can exploit the benefits of virtualization technologies to significantly reduce the energy consumption of large scale network infrastructures. In addition, the EE control framework [47] shall provide the control sequence and procedures for controlling and managing energy efficiency, within self-managed automated edge systems. Virtualization provides a promising approach for consolidating multiple online services onto few computing resources within an enterprise data center. By dynamically provisioning VMs, consolidating the workload, and switching servers on/off as needed, service providers can maintain the desired QoS while achieving higher server utilization and EE. In [17], a dynamic resource provisioning framework for a virtualized computing environment is presented and it is experimentally validated on a small server cluster that provides online services. Along the lines of MEC [28, 36], the long-term short memory (LSTM) neural network is used for forecasting the traffic load and harvested energy, and then the limited lookahead control (LLC) technique uses the forecasted traffic load and harvested energy to obtain the best control input that will drive the edge systems into the desired behavior.

3. Mobile datasets for network solutions

To enable power transmission adaptation and load balancing across BSs, traffic load information (operator mobile traffic datasets) obtained from the EPC can be utilized to extract relevant demand patterns to design dynamic BS management mechanisms [48, 49]. Optimization based on mobile traffic datasets, obtained from multiple network elements described in [49], will make it possible to minimize the amount of time it takes to steer traffic on a real time basis, thus provisioning the network resources for computing and communication. From a networking perspective, the understanding and characterization of the traffic consumption within the network can pave the way towards more efficient and user/traffic-oriented networking solutions.

A greedy algorithm is used to estimate the energy savings through dynamic BS operation based on real cellular traffic traces and actual BS location, within an urban environment [48]. In addition, during crowded events (e.g., concerts and soccer games), MNs face voice and data traffic volumes that are often orders of magnitude higher than what they face during normal days. In [50], datasets usage show the potential of dynamically switching on/off BSs around a stadium (soccer field), as some of the BSs experience low traffic load during a large event. Moreover, it is shown that the use of real-world voice and data traces can provide insights about when to tune the radio resource allocation and to make use of opportunistic connection sharing (the aggregating of traffic from multiple devices into a single cellular connection) towards network improvement, without incurring any costs related to infrastructure changes [51]. To improve energy savings and guarantee QoS, within the MEC paradigm, in [28, 36] the traffic load and energy datasets (solar and wind) are used to provide a short-term forecast, that is then used by the foresighted optimization algorithm towards dynamic resource allocation.

4. Conclusion

Future mobile networks are envisioned to be softwarized and the network functions virtualized. In light of this evolution, MEC has emerged to enable ultra-low latency services, distributed intelligence, and location-aware data processing at the network edge. The foreseen dense deployment of base stations empowered with computation capabilities motivates the need for energizing the edge systems (BSs and MEC servers) with green energy (solar and/or wind energy) in order to minimize the carbon footprint and the dependence on the power grid. Moreover, the use of green energy promotes energy self-sustainability within the network. In order to improve the energy efficiency, mobile traffic datasets can be used to come up with traffic-oriented network management solutions. For dynamic resource management, over a look-ahead prediction horizon, machine learning methods and control-theoretic techniques (foresighted optimization) are foreseen as tools for edge network management, i.e., for green energy-aware network apparatuses.

Author details

Thembelihle Dlamini
University of Padova, Padova, Italy

*Address all correspondence to: dlamini@dei.unipd.it

References

[1] Virtualization for small cells: Overview. Small Cell Forum, Draycott, England, Tech. Rep.; 2015

[2] Thembelihle D, Rossi M, Munaretto D. Softwarization of mobile network functions towards agile and energy efficient 5G architectures: A survey. Wireless Communications and Mobile Computing. 2017;**2017**:21. Article ID: 8618364. DOI: 10.1155/2017/8618364

[3] Xin J, Li LE, Laurent V, Rexford J. Softcell: Scalable and flexible cellular core network architecture. In: ACM Conference on Emerging Networking Experiments and Technologies. Santa Barbara, USA; 2013

[4] Hawilo H, Shami A, Mirahmadi M, Asal R. NFV: State of the art, challenges, and implementation in next generation mobile networks (vEPC). IEEE Network. 2014;**28**(6):18-26. DOI: 10.1109/MNET.2014.6963800

[5] Yang C, Chen Z, Xia B, Wang J. When ICN meets C-RAN for HetNets: An SDN approach. IEEE Communications Magazine. 2015;**53**(11):118-125. DOI: 10.1109/MCOM.2015.7321980

[6] Agyapong PK, Iwamura M, Staehle D, Kiess W, Benjebbour A. Design considerations for a 5G network architecture. IEEE Communications Magazine. 2014;**52**(11):65-75. DOI: 10.1109/MCOM.2014.6957145

[7] Unlock New Business Opportunities With vEPC. VMware, USA, Tech. Rep.; 2016

[8] 5G Mobile Communications Systems for 2020 and beyond. Fifth generation mobile promotion forum, Japan, Tech. Rep.; 2016

[9] Nakao A, Ping D, Masayuki K. Flare: Deeply programmable network node architecture. EU-Japan Collaboration Project, University of Tokyo, Japan; 2016. [Online]. Available from: http://www.5gsummit.org/berlin/docs/slides/Aki-Nakao.pdf

[10] M-CORD Open Reference Solution Paves the Way for 5G Innovation. 2016. [Online]. Available from: http://opencord.org/tag/m-cord/

[11] Nakao A. Software-defined data plane enhancing SDN and NFV. IEICE Transactions on Communications. 2015;**98**(1):12-19. DOI: 10.1587/transcom.E98.B.12

[12] Kekki S, Featherstone W, Fang Y, Kuure P, Li A, Ranjan A et al. MEC in 5G Networks. ETSI, Sophia-Antipolis, France, Tech. Rep.; 2018

[13] Patel M, Hu Y, Hédé P, Joubert J, Thornton C, Naughton B et al. Mobile edge computing introductory technical white paper. ETSI, Sophia-Antipolis, France, Tech. Rep.; 2014

[14] Lu G, Guo C, Li Y, Zhou Z, Yuan T, Wu H et al. ServerSwitch: A programmable and high performance platform for data center networks. In: USENIX Conference on Networked Systems Design and Implementation. Boston, USA; 2011

[15] Nunes BAA, Mendonca M, Nguyen XN, Obraczka K, Turletti T. A survey of software-defined networking: Past, present, and future of programmable networks. IEEE Communication Surveys and Tutorials. 2014;**16**(3):1617-1634. DOI: 10.1109/SURV.2014.012214.00180

[16] Ciosi M, Clarke D, Cui C, Benitez J, Mivhel U, Ogaki K et al. Introductory white paper: Network functions virtualization. In: SDN and Open Flow World Congress. Darmstadt, Germany; 2012

[17] Kusic D, Kephart JO, Hanson JE, Kandasamy N, Jiang G. Power and performance management of virtualized computing environments via lookahead control. In: International Conference on Autonomic Computing, Chicago, USA; 2008

[18] Bhushan N, Li J, Malladi D, Gilmore R, Brenner D, Damnjanovic A, et al. Network densification: The dominant theme for wireless evolution into 5G. IEEE Communications Magazine. 2014;**52**(2):82-89. DOI: 10.1109/MCOM.2014.6736747

[19] Morabito R. Power consumption of virtualization technologies: An empirical investigation. In: IEEE International Conference on Utility and Cloud Computing (UCC). Limassol, Cyprus; 2015

[20] Jin Y, Wen Y, Chen Q. Energy efficiency and server virtualization in data centers: An empirical investigation. In: IEEE Conference on Computer Communications Workshops (INFOCOM Workshops). Orlando, USA; 2012

[21] Portnoy M. Virtualization Essentials. Indianapolis, Indiana, USA: John Wiley & Sons; 2012

[22] Wu B, Fu S, Jiang X, Wen H. Joint scheduling and routing for QoS guaranteed packet transmission in energy efficient reconfigurable WDM mesh networks. IEEE Journal on Selected Areas in Communications. 2014;**32**(8):1533-1541. DOI: 10.1109/JSAC.2014.2335313

[23] Fu S, Wen H, Wu J, Wu B. Cross-networks energy efficiency trade-off: From wired networks to wireless networks. IEEE Access. 2017;**5**:15-26. DOI: 10.1109/ACCESS.2016.2585221

[24] Network Functions Virtualisation (NFV): Hypervisor Domain. ETSI, Sophia-Antipolis, France, Tech. Rep.; 2015

[25] Cisco visual networking index: Forecast and Methodology, 2017-2022. Cisco, Tech. Rep.; 2019

[26] Dlamini T, Gambin AF. Adaptive resource management for a virtualized computing platform in edge computing. In: IEEE International Conference on Sensing, Communication and Networking (SECON). Boston, USA; 2019

[27] Gabriel B. Mobile edge computing use cases and deployment options. Heavy Reading, Tech. Rep.; 2016

[28] Dlamini T, Gambín ÁF, Munaretto D, Rossi M. Online resource management in energy harvesting BS sites through prediction and soft-scaling of computing resources. In: IEEE PIMRC. Bologna, Italy; 2018

[29] Shojafar M, Cordeschi N, Amendola D, Baccarelli E. Energy-saving adaptive computing and traffic engineering for real-time-service data centers. In: IEEE International Conference on Communication Workshop (ICCW), London, UK; 2015

[30] Bousia A, Kartsakli E, Antonopoulos A, Alonso L, Verikoukis C. Multi-objective auction-based switching-off scheme in heterogeneous networks: To bid or not to bid? IEEE Transactions on Vehicular Technology. 2016;**65**(11):9168-9180. DOI: 10.1109/TVT.2016.2517698

[31] Dongsheng Han BZ, Chen Z. Sleep mechanism of base station based on minimum energy cost. Wireless Communications and Mobile Computing. 2018;**2018**:13. Article ID: 4202748. DOI: 10.1155/2018/4202748

[32] Zhu Y, Zeng Z, Zhang T, An L, Xiao L. An energy efficient user association scheme based on cell sleeping in LTE heterogeneous networks. In: International Symposium on Wireless Personal Multimedia

Communications (WPMC). Sydney, Australia; 2014

[33] Zhang H, Cai J, Li X. Energy-efficient base station control with dynamic clustering in cellular network. In: IEEE International Conference on Communications and Networking (CHINACOM). Guilin, China; 2013

[34] Samarakoon S, Bennis M, Saad W, Latva-aho M. Dynamic clustering and ON/OFF strategies for wireless small cell networks. IEEE Transactions on Wireless Communications. 2016;**15**(3):2164-2178. DOI: 10.1109/TWC.2015.2499182

[35] Oh E, Son K, Krishnamachari B. Dynamic base station switching-on/off strategies for green cellular networks. IEEE Transactions on Wireless Communications. 2013;**12**(5):2126-2136. DOI: 10.1109/TWC.2013.032013.120494

[36] Dlamini T, Gambín ÁF, Munaretto D, Rossi M. Online supervisory control and resource management for energy harvesting BS sites empowered with computation capabilities. Wireless Communications and Mobile Computing. 2019;**2019**:17. Article ID: 8593808. DOI: 10.1155/2019/8593808

[37] Han T, Ansari N. A traffic load balancing framework for software-defined radio access networks powered by hybrid energy sources. IEEE/ACM Transactions on Networking. 2016;**24**(2):1038-1051. DOI: 10.1109/TNET.2015.2404576

[38] Xu J, Wu H, Chen L, Shen C, Wen W. Online geographical load balancing for mobile edge computing with energy harvesting. arXiv preprint arXiv:1704.00107; 2017

[39] Antonopoulos A, Kartsakli E, Bousia A, Alonso L, Verikoukis C. Energy-efficient infrastructure sharing in multi-operator mobile networks. IEEE Communications Magazine. 2015;(5):242-249. DOI: 10.1109/MCOM.2015.7105671

[40] Oikonomakou M, Antonopoulos A, Alonso L, Verikoukis C. Evaluating cost allocation imposed by cooperative switching off in multi-operator shared HetNets. IEEE Transactions on Vehicular Technology. 2017;**66**(12):11352-11365

[41] Xu J, Ren S. Online learning for offloading and autoscaling in renewable-powered mobile edge computing. In: IEEE Global Communications Conference (GLOBECOM). Washington, USA; 2016

[42] Shojafar M, Cordeschi N, Baccarelli E. Energy-efficient adaptive resource management for real-time vehicular cloud services. IEEE Transactions on Cloud Computing. 2016;**7**(1):196-209. DOI: 10.1109/TCC.2016.2551747

[43] Guenter B, Jain N, Williams C. Managing cost, performance, and reliability tradeoffs for energy-aware server provisioning. In: Proceedings IEEE INFOCOM. Shanghai, China; 2011

[44] Beloglazov A, Abawajy J, Buyya R. Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing. Future Generation Computer Systems. 2012;**28**(5):755-768

[45] Nathuji R, Schwan K. VirtualPower: coordinated power management in virtualized enterprise systems. In: ACM SIGOPS symposium on Operating systems principles. Washington, USA; 2007

[46] ETSI GS MEC: Mobile Edge Computing (MEC); Framework and Reference Architecture. ETSI, France, Tech. Rep.; 2016

[47] Study on Energy Efficiency Aspects of 3GPP (3GPP TR 21.866 - Release 14). ETSI, France, Tech. Rep.; 2016

[48] Oh E, Krishnamachari B, Liu X, Niu Z. Toward dynamic energy-efficient operation of cellular network infrastructure. IEEE Communications Magazine. 2011;**49**(6). DOI: 10.1109/MCOM.2011.5783985

[49] Charging management; Charging Data Record (CDR) parameter description (3GPP TS 32.2 .298 version 13.5.0 Release 13). ETSI, France, Tech. Rep.; 2016

[50] Erman J, Ramakrishnan KK. Understanding the super-sized traffic of the super bowl. In: Proceedings of the 2013 conference on Internet measurement conference. Barcelona, Spain; 2013

[51] Zubair SM, Lusheng J, X LA, Jeffrey P, Shobha V, Jia W. A first look at cellular network performance during crowded events. ACM Sigmetrics Performance Evaluation Review. 2013;**41**(1):17-28