Planning of Dynamic Mobile Optical Virtual Network Infrastructures Supporting Cloud Services

M. P. Anastasopoulos, A. Tzanakaki, B. Rofoee, S. Peng, G. Zervas, D. Simeonidou, G. Landi, G. Bernini, N. Ciulli, J.F. Riera, E. Escalona, J. A. Garcia-Espin, K. Katsalis, T. Korakis

Abstract—This paper proposes a next generation ubiquitous converged infrastructure to support Cloud and mobile Cloud computing services. The proposed infrastructure facilitates interconnection of fixed and mobile end users with computational resources through a heterogeneous network integrating optical metro and wireless access networks. To satisfy the low-latency requirements of content-rich mobile applications, a novel stochastic virtual infrastructure planning model that takes a holistic approach considering jointly the network and computational resources is presented. Our modelling results identify trends and trade-offs related to end-to-end service delay, resource requirements and energy consumption levels of the infrastructure across the various technology domains under traffic uncertainty.

I. INTRODUCTION

It is predicted that the number of end devices connected to the Internet coupled with the rapid rise of BigData and Cloud-based services, will result in increasingly vast volumes of data that are expected to exceed 1 zettabyte per year by 2016 [1] and require to be transported to remote locations across an interconnecting network infrastrucutre. In addition, mobile internet users are expected to experience a dramatic growth, introducing a huge increase in mobile data, a big part of which will come from Cloud computing applications [2]. To address these emerging requirements the concept of Mobile Cloud Computing (MCC), where computing power and data storage are moving away from mobile devices to remote computing resources has been introduced [3].

As the volume and diverse requirements of these data cannot be intrinsically supported by the current best effort Internet, there is a need for a paradigm shift for the interconnecting infrastructure. This infrastructure needs to offer intelligent and ubiquitous connectivity and support quality of service guaranteed end-to-end services. To enable efficient and sustainable operation this infrastructure also needs to ensure flexible allocation of heterogeneous yet coordinated resources facilitating convergence between traditionally separate network domains/technologies and data infrastructures.

Existing mobile cloud computing solutions allow mobile devices to access the required resources by accessing a nearby resource-rich cloudlet, rather than relying on a distant "cloud," [4]. In order to satisfy the low latency requirements of several content-rich mobile cloud computing services [5], one-hop,
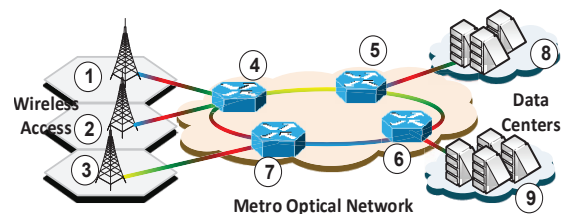
Fig. 1. Physical Infrastructure

high-bandwidth wireless access to the cloudlet is required. In the case where a cloudlet deploying small data centres (DCs) is not available nearby, traffic is offloaded to a distant cloud such as Amazons Private Cloud, GoGrid [6] or Flexigrid [7]. However, the lack of service differentiation mechanisms for mobile and fixed cloud traffic across the various network segments involved, the varying degrees of latency at each technology domain and the lack of global optimization tools in the infrastructure management and service provisioning phases make the current solutions inefficient. To address these issues, a next generation ubiquitous converged infrastructure suitable to support cloud and mobile cloud computing services has been proposed in the context of the European project CONTENT [8] (Fig. 1). This infrastructure facilitates the interconnection of data centres (DCs) with fixed and mobile end users through a heterogeneous network integrating optical metro and wireless access network technologies. The proposed architecture integrates an advanced optical network solution offering fine (sub-wavelength) switching granularity with a wireless access network supporting end user mobility. To support the Infrastructure as a Service (IaaS) paradigm as well as the diverse QoS needs of future Cloud and mobile Cloud services, the concept of virtualization across all technology domains is adopted.

In this paper, we present in detail the CONTENT converged network infrastructure as well as the details of layered architecture proposed to support efficiently and effectively cloud and mobile cloud services. As in the context of the CONTENT architecture cross-domain virtualization is a key enabling technology, this paper also presents a novel virtual infrastructure (VI) planning scheme that takes a holistic approach considering jointly the network and DC segments. The adoption of this approach ensures allocation of the required resources across all domains extending the work presented in [8]. In addition, it enables the support of service requests and their specific characteristics such as low latency, QoS differentiation and mobility of end users and facilitates globally optimized solutions in terms of objectives such as energy

Fig. 2. The CONTENT architecture

Fig. 3. Prediction of the VI traffic and mapping of the VI resources onto the multi-queuing model of the converged architecture presented in Fig.1
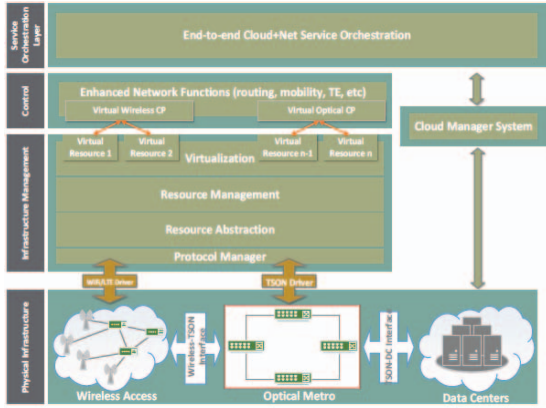
consumption and resource allocation. Our modeling results identify trends and trade-offs relating to resource requirements and energy consumption levels across the various technology domains involved that are directly associated with the services characteristics.

The remaining of this document is structured as follows: Section II provides a description of the proposed architecture. Section III, includes a discussion on the modelling framework developed with the aim to evaluate the CONTENT architecture and the associated results. Numerical results are provided in Section IV. Finally, Section V summarizes the conclusions.

II. VISION AND ARCHITECTURAL APPROACH

The infrastructure model proposed by CONTENT is based on a layered architecture (Fig.2). To support the IaaS paradigm, physical resource virtualization, generating virtual infrastructure slices, is enabled by a cross-domain infrastructure management layer. Connectivity services are provided over the virtual infrastructure slices, through the virtual infrastructure control layer. Integrated end-to-end network, cloud and mobile cloud services are orchestrated and provisioned through the service orchestration layer. More details on the individual architecture layers are provided below.

A. Physical Infrastructure Layer

The heterogeneous physical infrastructure comprises a hybrid wireless access network (LTE/WiFi) domain, and an optical metro network domain interconnecting geographically distributed DCs. The optical metro network is based on the Time Shared Optical Network (TSON) technology supporting frame-based sub-wavelength switching granularity [10]. TSON offers connectivity to the wireless access and DC domains by providing flexible rates and a virtualisation friendly transport technology. The wireless access part comprises a converged 802.11 and 4G (LTE) access technology network, used to support cloud computing services through the NITOS wireless testbed [11]. The backhaul network comprises the packet core network that is used to transport traffic to the Gateway that will interact with the TSON optical network Gateway.

B. Infrastructure management

The Infrastructure Management Layer (IML) is the responsible to provide management of the physical resources. The IML
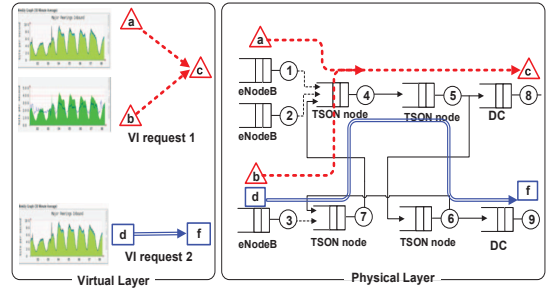
functionality is twofold. On the one hand, it is the element of the architecture devoted to the converged management (e.g. monitoring, abstraction, discovery, or lifecycle management) of physical resources populating different technology domains. On the other hand, it is responsible for the creation of isolated virtual infrastructures composed of resources belonging to different technology domains. Additionally, the management layer, which lies directly over the physical infrastructure, deploys the Cloud Management System (CMS). CMS is used to facilitate management of computational resources.

C. Virtual Infrastructure Control Layer

The converged Virtual Infrastructures, delivered through the Infrastructure Management Layer described in the previous section, are jointly operated through a unified control layer based on the Software Defined Networking (SDN) paradigm. This layer, called Virtual Infrastructure Network Control Layer, implements converged control and management procedures for dynamic and automated provisioning of end-to-end connectivity in support of QoS-guaranteed cloud services for fixed and mobile users. The network services span across the wireless and metro networks, and are coordinated to provide efficient utilization of the overall virtual network resources.

D. Service Orchestration Layer

On top of the Virtual Infrastructure Network Control Layer, a Service Orchestration Layer is in charge of composing and delivering cloud services to the mobile end-users, properly integrated with dedicated wireless connectivity services. The Service Orchestration Layer combines network and cloud resources available in the Virtual Infrastructure, and provides a complete and converged cloud service that matches the users requirements. Cooperation between the control and the orchestration layers is the key factor for consistent and converged management of the entire Virtual Infrastructure.

III. DYNAMIC MOBILE VIRTUAL INFRASTRUCTURE PLANNING

A. Problem description

This section deals with the problem of planning VIs over an integrated platform comprising a cellular LTE system for the wireless access domain and an optical metro network that interconnects the wireless access domain with the computing

resources. Its objective is to identify the topology and determine the virtual resources required to implement dynamically reconfigurable VIs over the underlying converged infrastructures. Each VI not only has to meet user specific needs, but also has to support resource utilization efficiency. In such a highly dynamic and heterogeneous network environment the optimal VI planning problem is complex since information regarding the position and the application requirements of the mobile devices, the performance of the optical and the wireless network domains as well as the availability of resources in the network and the DCs are uncertain. In order to assess the performance requirements of this type of VIs, a stochastic optimization modeling framework suitable for VI planning is proposed that takes into account the varying degrees of latencies introduced by all technology domains involved as well as the time variability and uncertainty of services.

It should be mentioned that throughout the planning process, the virtual traffic requirements need to either be known in advance or predicted based on history observations. This could be achieved by taking a weighted average of the traffic demands over the most recent time periods e.g. using autoregressive method moving average methods (ARMA). Once this information becomes available, the optimal VIs that can support the required services are identified in terms of both topology and resources. This process ensures that the planned VIs have sufficient network capacity for all demands to be transferred to the computing servers, and adequate computing server resources such as CPU, memory, disk storage to support all requested services satisfying, at the same time, specific end-to-end delay requirements.

B. Mathematical Modeling

The VI planning problem is mathematically formulated adopting a multi-layer approach in which the lower layer contains the physical infrastructure (PI) resources while the upper layer a set $\mathcal{I}$ of I VIs $\mathcal{I} = (1, \ldots, I)$. The PI is represented as a weighted graph $\mathcal{G}^p = (\mathcal{N}^p, \mathcal{E}^p)$ where $\mathcal{N}^p$ represents the set of PI nodes and $\mathcal{E}^p$ the set of PI links. Each VI_i ($i \in \mathcal{I}$) is modeled as an undirected graph $\mathcal{G}_i^v = (\mathcal{N}_i^v, \mathcal{E}_i^v, \mathcal{D}_i)$ where $\mathcal{N}_i^v, \mathcal{E}_i^v$ are used to denote the set of nodes and links, respectively, and $\mathcal{D}_i$ is used to describe the set of demands. These demands may arise either from the optical or the wireless domain and need to be served by a set $\mathcal{S}$ of S geographically distributed DCs $\mathcal{S} = (1, \ldots, S)$. Given that in MCC applications not only the requested infrastructure capacity but also the location of the mobile computing devices is uncertain, information regarding the traffic volume H_{di} of a demand d ($d \in \mathcal{D}_i$) originating from VI_i is not precisely available. However, this parameter can be described by a probability distribution function (pdf) that can be estimated based on history observations. To this end, the random vector ξ is introduced that contains all the uncertain parameters that are involved in the planning process. In the present study, ξ is described through a finite number of possible realizations, called scenarios, say $\xi = (\xi_1, \xi_2, \ldots, \xi_K)$, with probabilities $p_r(\xi) \in [0, 1]$. Hence, H_{di} are scenarios in ξ, namely $H_{di}(\xi)$, with known pdfs.

At the same time, the traffic demands need to be realized within a specific timeframe $\mathcal{T}$. Therefore, during the planning process, the requested resources will be rearranged based on service-specific constraints, satisfying at the same time the *scheduling constraints*:

$$\sum_t \gamma_{dti} h_{dti}(\xi) = H_{di}(\xi), \ d \in \mathcal{D}_i, i \in \mathcal{I}, t \in \mathcal{T} \quad (1)$$

In (1), γ_{dti} is a binary variable indicating whether demand d of VI_i can be realized a time $t \in \mathcal{T}$ and $h_{dti}(\xi)$ is the volume of demands that are scheduled at time t for the scenario ξ.

In the general case, the VI planning problem should be solved taking into account a set of constraints that will be satisfied with a high probability, and ensure the efficient and stable operation of the resulting infrastructures, including constraints that:

1. Ensure with a specific *availability threshold* that the allocated virtual resources are sufficient to handle the foreseeable service requests.
2. Assign each demand to a single server for processing.
3. Ensure that the planned VIs have sufficient capacity for all demands to be transferred to their destinations.
4. Ensure that the capacity of each link in the VI is realized by specific PI resources. At the same time, the planned VI has adequate DC server resources such as CPU, memory, disk storage to support all requested services.
5. Limit the total delay introduced by the heterogeneous technology domains below a specific threshold. This constraint plays a key role in the VI planning process as it affects the decision of a mobile device to offload or not its traffic requests in the cloud. For example, if end-to-end delays are high, demands will be not offloaded to the cloud as there is increased probability that their corresponding QoS constraints will be violated

In order to mathematically formulate these constraints, the following parameters/variables are introduced:

- a_{dsi} that is a binary variable taking value equal to 1 if demand d of VI_i is assigned to server s; 0 otherwise,
- $\mathcal{P}_{dtsi}$ that is a set containing all the possible paths in the virtual layer that can be used in order to transfer the traffic volume h_{dti} to the server s at time t,
- x_{dpti} that is the flow realizing demand d on path $p \in \mathcal{P}_{dtsi}$ at time t,
- y_{eti} representing the virtual capacity of link e that can support all demands of the VI_i at time period t and,
- δ_{edpti} is a binary coefficient taking value equal to 1 if link e of VI_i belongs to path p realizing demand d at server s; 0 otherwise,

Based on these parameters and after employing the link-path formulation approach, the single server allocation, the demands conservation, as well as, the capacity constraints in the virtual layer can be described for all possible scenarios ξ through equations (2)-(4):

$$\sum_s a_{dsi} = 1, \ d \in \mathcal{D}_i, i \in \mathcal{I} \quad (2)$$

$$\sum_s \sum_p a_{dsi} x_{dpti}(\xi) = h_{dti}(\xi), \ d \in \mathcal{D}_i, i \in \mathcal{I}, t \in \mathcal{T} \quad (3)$$

$$\sum_d \sum_p \delta_{edpti} x_{dpti}(\xi) \le y_{eti}(\xi), \ e \in \mathcal{E}_i^v, \ i \in \mathcal{I}, \ t \in \mathcal{T}$$
(4)

Following the same rationale, the necessary resources in the physical layer can be also identified. Initially, the virtual capacities $y_{eti}(\xi)$ are treated as demands that need to be supported by specific PI resources and a set of equations similar to (2)-(4) can be extracted. Besides network capacity constraints, the total requested processing power at each server s should not exceed its processing capacity.

So far, the proposed scheme ensures that there are sufficient network and processing capacities to support the requested services. Apart from network bandwidth requirements, end-to-end delay guarantees should be also provided. However, given that in highly loaded networks queuing delay is the dominant part of the end-to-end delay, the VI Control Layer described in Sec.II needs to be considered by applying relevant delay constraints in the service provisioning process across all the technology domains involved. These constraints should allow the VIs to reserve a specific portion of the receivers'/transmitters' queues at a TSON edge node or at an eNodeB, with the objective to maintain the end-to-end delay below a predefined threshold.

In order to mathematically formulate this issue, the PI is modeled as an open queuing network, in which its node $n \in \mathcal{N}^p$ has m_n service modules (in the wireless access domain, m_n corresponds to the number of input queues at an eNodeB, while in the optical domain it corresponds to the number of receiver/transmitter queues in the TSON edge node) with service rate μ_n. Due to the uncertainties introduced in MCC environments, we consider the general case where the inter-arrival times of the demands are not necessarily exponentially distributed. Assuming that:

- the external arrival process of the demands of VI_i is any renewal process with mean inter-arrival time $1/\lambda_i$ and coefficient of variation σ_{Ai} (both parameters are estimated based on the ARMA model),
- the service times at the nth node of the PI can follow any distribution with mean service time $1/\mu_n$ and coefficient of variation σ_{Bn} and,
- the demands are served according to the First In First Out policy,

an approximation for the end-to-end delay for the services that are provided by each VI can be extracted after applying the *method of decomposition* [12]. This method is based on the following steps [13]:

1. The arrival rate, λ_{ni}, and the utilization, ρ_{ni}, for the demands of VI_i at the nth node of the PI are calculated
2. Once the λ_{ni}, ρ_{ni} have been determined, the coefficient of variation of the interarrival times at each node n, namely σ_{Ani}, is determined using an iterative process that consists of the following phases: i) *Merging Phase*: Traffic requests that arrive at each node are merged into a single arrival process. $\sigma_{Ani}, \lambda_{ni}$ can be estimated using various approximation formulas. In the present work, the decomposition method presented in [14] has been adopted. ii) *Flow Phase*: The coefficient of variation for the inter-departure times at each node are estimated

using as input the coefficient of variation of the inter-arrival times σ_{Ani} as well as the coefficient of variation for the service times. iii) *Splitting Phase*: In this phase, the served demands are forwarded to the subsequent nodes for processing.

3. In the final step, using as input the parameters σ_{Ani} and λ_{ni}, the mean queue length and, consequently, the average waiting time per node can be evaluated using the well-known formulas for *GI/G/m* e.g.,

$$\overline{W}_{ni} = \frac{P_{m_{ni}}/\mu_{ni}}{1 - \rho_{ni}} \frac{\sigma_{Ani}^2 + \sigma_{Bni}^2}{2m_{ni}}$$

where

$$P_{m_{ni}} = \frac{(m_{ni}\rho_{ni})^{m_{ni}}}{m_{ni}!(1 - \rho_{ni})} \pi_0$$

Finally, in order to bound the end-to-end cloud delay of the services offered by VI_i below a specific threshold, $\mathcal{L}_i$, the following constraint should be satisfied:

$$\sum_n \theta_{in} \overline{W}_{ni} \le \mathcal{L}_i, i \in \mathcal{I}$$
(5)

where θ_{in} is a binary parameter taking value equal to 1 if node $n \in \mathcal{N}^p$ is used by VI_i.

Closing the analysis, the optimal VIs are obtained by minimizing the expected cost:

$$\min \mathbb{E}[Q(\mathbf{w}, \mathbf{u}; \xi)]$$
(6)

where

$$Q(\mathbf{w}, \mathbf{u}; \xi) = \min \sum_t \mathcal{N}_t(\mathbf{w}, \xi) + \sum_t \mathcal{S}_t(\mathbf{u}, \xi)$$
(7)

In (7), $\mathcal{N}_t$ is the power consumption of the network resources $\mathbf{w}$ at time t and $\mathcal{S}_t$ the power consumption cost of computing resources $\mathbf{u}$ at time t.

IV. NUMERICAL RESULTS

The performance of the proposed VI planning scheme across the multiple domains involved is studied based on the infrastructure illustrated in Fig. 1. For the PI, a macro-cellular network with regular hexagonal cell layout has been considered similar to that presented in [15], consisting of 12 sites, each with 3 sectors and 10MHz bandwidth, operating at 2.1 GHz. The inter-site distance has been set to 500m to capture to scenario of a dense urban network deployment. Furthermore, a 2x2 MIMO transmission has been considered, while the users are uniformly distributed over the serviced area. Each site can process up to 115 Mbps and its power consumption ranges from 885 to 1087W, under idle and full load, respectively [15]. For the computing resources, three "*Sun Oracle Database Machine Basic Systems*" [16] have been considered where each server can process up to 36Gbps of compressed flash data. The physical TSON topology assumed is illustrated in the right part Fig.3 where the dimensions of the optical rings are below 5 km and the supported data rate is 8.68Gbps. The power consumption of the TSON equipment is measured to be 50W for the EDFAs and 100mW for the PLZT chip.

Initially, the total power consumption of the converged infrastructure (wireless access, optical network and IT resources)
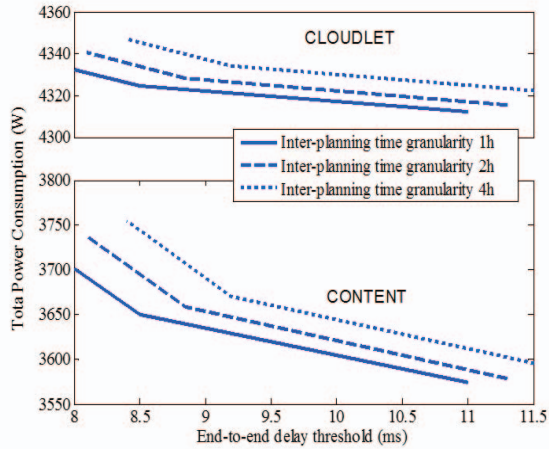
Fig. 4. Energy-delay trade-offs for various inter-planning time granularities (Average Mobile cloud demand volume 10MB, availability threshold 95%)
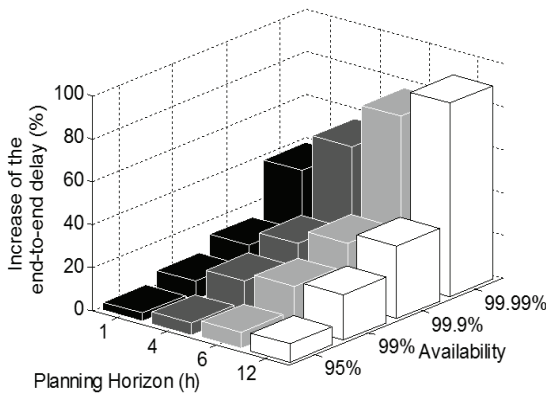

Fig. 5. Increase of the end-to-end delay different planning horizons and availability requirements (Average Mobile cloud demand volume 30MB Average Fixed Cloud Demand volume 1GB- All PI resources are leased)

as a function of the end-to-end delay threshold when applying the proposed and the cloudlet approach is depicted in Fig.4. It is observed that the proposed solution consumes significantly lower energy (corresponding to lower operational cost) to serve the same amount of demands compared to the cloudlet. This is due to that, in the former approach fewer DC servers are activated to serve the same amount of demands. Another interesting observation is that with the increase of the inter-planning time granularity the overall power consumption is increased. This is explained by the fact that with the increase of the planning horizon from 1 to 4 hours the prediction error also increases leading to a significant increase in the computing and network resources that need to be allocated to cope with the uncertainty of demands. From the same figure it is also observed that the total power consumption is very much dependent on the end-to-end delay constraints. For example, services with strict packet delay constraints require high levels of power to operate. However, when this constraint is relaxed the total power consumption is decreased. In order to satisfy services with strict end-to-end delay constraints, the long waiting times in the queues should be avoided. To achieve this, additional resources need to be assigned to the VIs leading to increased service rates and increased power consumption.

In Fig.5 the impact of the planning horizon on the end-to-end delay is studied for various availability levels. It is observed that with the increase of the planning horizon, the uncertainty of the traffic demands is increased, leading to an increase of the end-to-end delays. This is explained by the fact that for larger variances, the demand requests experience longer waiting times in the queues and, consequently, increased end to end delays.

V. CONCLUSIONS

This paper studied the problem of virtual infrastructure planning over converged wireless, optical network and computing resources. A novel problem formulation based on stochastic programming has been presented in order to minimize the energy consumption of the converged infrastructures satisfying at the same time specific QoS specifications. Numerical results indicate that there are a number of trade-offs relating to end-to-end service delay, resource requirements and energy consumption levels of the infrastructure across the various technology domains closely associated with the service characteristics.

REFERENCES

[1] M. Rappa, "The utility business model and the future of computing systems," *IBM Systems Journal*, 43 (1), 32-42, 2004.

[2] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 20122017, White Paper, 2013

[3] H. Dinh, C. Lee, D. Niyato, P. Wang, "A survey of mobile cloud computing: architecture, applications, and approaches," *Wirel. Commun. Mob. Comput.* Oct. 2011

[4] M. Satyanarayanan et al.,The Case for VM-Based Cloudlets in Mobile Computing. *IEEE Perv. Comp.* 8 (4), pp.14-23, 2009

[5] K. Mun, "Mobile Cloud Computing Challenges, TechZine Magazine, http://www2.alcatel-lucent.com/techzine/mobile-cloud-computing-challenges/

[6] http://www.gogrid.com/

[7] http://www.flexiscale.com/

[8] A. Tzanakaki et.al., "Virtualization of heterogeneous wireless-optical network and IT infrastructures in support of cloud and mobile cloud services, *IEEE Commun. Magazine*. vol.51, no.8, pp.155-161, Aug. 2013

[9] CONTENT D4.1, Definition of the virtualization strategy and design of domain specific resources/services virtualization in CONTENT, 2013

[10] MAINS project website, http://www.ist-mains.eu/

[11] D. Giatsios et.al.,"Methodology and tools for measurements on wireless testbeds: The nitos approach, in M*easurement Methodology and Tools, LNCS*, Springer Berlin heidelberg, 2013, vol. 7586, pp. 6180.

[12] R. Bruno et.al.,"A Queuing Modeling Approach for Load-Aware Route Selection in Heterogeneous Mesh Networks, *IEEE WoWMoM* 2009.

[13] P. Kuehn, "Approximate Analysis of General Queuing Networks by Decomposition, *IEEE Trans. Commun.*, 27(1), 113-126, 1979

[14] G. Pujolle, W.Ai, "A Solution for Multiserver and Multiclass Open Queueing Networks, *INFOR*, Vol.24(3), .221-230, 1986

[15] G. Auer, V. Giannini, "Cellular Energy Efficiency Evaluation Framework", *in Proc. of IEEE VTC* 2011

[16] http://www.oracle.com/us/industries/healthcare /058454.pdf?ssSourceSiteId=ocomjp