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Wireless-Optical Network Convergence: Enabling the 5G Architecture to Support Operational and End-User Services

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Abstract— **This paper presents a converged 5G network infrastructure and an overarching architecture, to jointly support operational network and end-user services, proposed by the EU 5G PPP project 5G-XHaul. The 5G-XHaul infrastructure adopts a common fronthaul/backhaul network solution, deploying a wealth of wireless technologies and a hybrid active/passive optical transport, supporting flexible fronthaul split options. This infrastructure is evaluated through a novel modeling. Numerical results indicate significant energy savings at the expense of increased end-user service delay.**

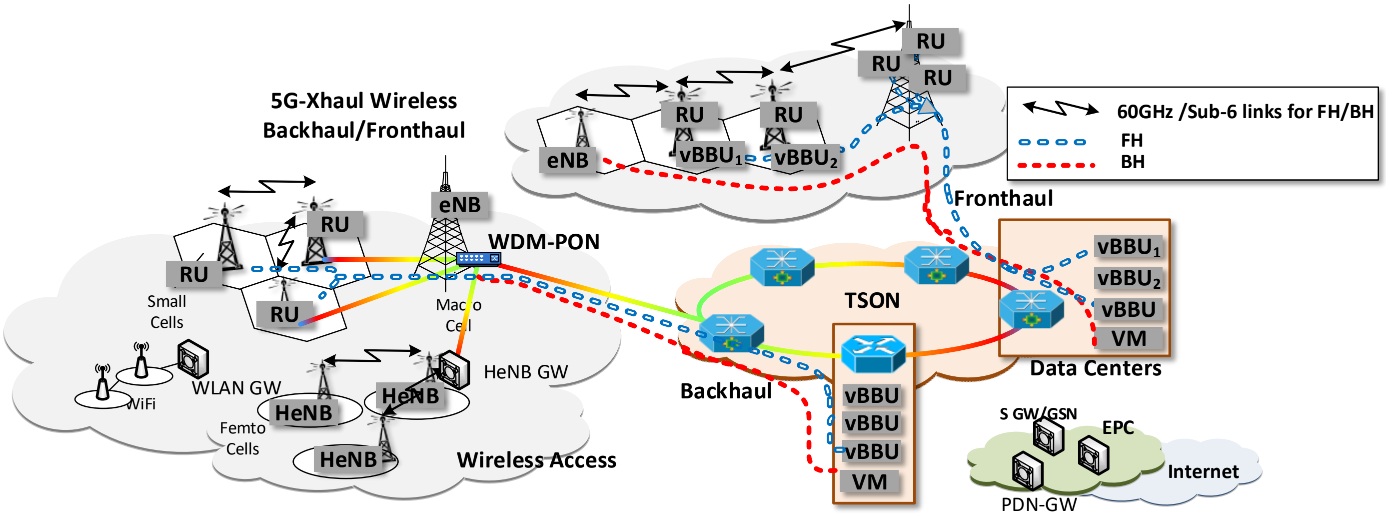
***Keywords*—5G, backhauling, fronthauling, small cells, C-RAN**

I. INTRODUCTION

The enormous growth of mobile data predicted is attributed to the rapidly increasing: a) number of network-connected end devices, b) Internet users with heavy usage patterns, c) broadband access speed, and d) popularity of applications such as cloud computing, video, gaming etc. Traditional Radio Access Networks (RANs), where Base Band Units (BBUs) and radio units (RUs) are co-located, cannot meet this massive foreseen growth. This is attributed to high capital and operational costs associated with the lack of resource sharing and modularity, reduced agility and scalability as well as inefficient energy management.

Cloud Radio Access Networks (C-RANs) propose to overcome these limitations, by supporting connection of Access Points (APs), known as RUs, to a BBU pool hosted in a Central Unit (CU) through a set of transport links. These links are referred to as fronthaul (FH). Currently interfacing between RUs and CU is enabled through the adoption of standards such as the Common Public Radio Interface (CPRI). The RU wireless signals are commonly transported over an optical FH network, using either digital transmission (e.g. CPRI), or analog transmission (radio-over-fiber). The adoption of CPRI type of solutions enables consolidation of a larger number of BBUs per CU by extending the transport network range. However, C-RAN requires very high transport bandwidth due to the traffic volume created by the sampled radio signals transported to the CU and the very tight delay and synchronization specifications [1]. Existing mmWave E-Band and optical transport solutions supporting traditional backhaul (BH) requirements are based on different flavours of Passive Optical Networks (PONs) and 10GE technologies. Considering that in 5G environments these transport solutions will also need to offer FH capabilities, it is clear that they will be unable to offer the required capacity for both BH and FH services. To take advantage of the benefits and address the challenges associated with C-RAN, equipment vendors are expanding their FH solutions adopting advanced wireless technologies (e.g. Sub-6GHz and 60GHz bands, including advanced beam tracking and MIMO techniques), and new flexible and dynamic Wavelength Division Multiplexing (WDM) optical networks [2]. These are also enhanced with novel control and management approaches to enable increased granularity, end-to-end optimization and guaranteed Quality of Service (QoS).

To facilitate CRAN's technical feasibility and benefit from its coordination and pooling gains there is a need to relax the FH requirements. In view of this, solutions proposing FH compression and alternative architectures relying on flexible functional splits (Figure 2) have been reported [3], [4]. The concept of flexible splits relies on transferring some of the processing functions away from the RU and locating these centrally at a CU. These functions are commonly performed through dedicated and specific purpose hardware, with significant installation, operational and administrative costs. To address these issues, the concept of *network softwarisation* enabling migration from traditional closed networking models to an open reference platform able to instantiate a variety of network functions has been recently proposed. A typical example includes the OpenAirInterface (OAI) i.e. an open source 4G/5G radio stack able to be executed on general purpose servers hosted in data centers (DCs) [5]. Such open source frameworks are still in early development stages and do not allow execution of more complex functionalities such as flexible RAN splits. In this study, the concept of flexible functional splits is addressed by appropriately combining servers with low processing power (cloudlets) and relatively large-scale DCs placed in the access and metro domains respectively. The remote processing requirements associated with some of the functional split options, impose the need for a high bandwidth transport interconnecting RUs and the CU. On the other hand, the variability of remote processing requirements across the various split options introduce the need for a transport network that offers finely granular and elastic resource allocation capabilities.



HeNB: Home eNodeB
VM: Virtual Machine
GW: Gateway
vBBU: Virtual Base Band Unit
RU: Remote Unit
PDN-GW: Packet Data Network GateWay
EPC: Evolved Packet Core
S GW: Serving GateWay

Figure 1:The 5G-XHaul Physical Infrastructure: FH and BH services are provided over a common wired/wireless network infrastructure. In the FH case, parts of the BBU processing can be performed locally and some parts remotely at the DCs enabling the C-RAN flexible split paradigm. BBUs are executed in general purpose servers in the form of virtual entities. BH services interconnect end-users with Virtual Machines hosted in the DCs.

Addressing these challenges, we propose a network solution that converges heterogeneous network domains deploying optical and wireless technologies together with compute resources in a common 5G infrastructure. This infrastructure, developed in the framework of the EU 5G PPP project 5G-XHaul, will support both operational network as well as fixed and mobile end-user services. Operational network services refer to services required for the operation of the 5G infrastructure e.g. FH services offered to infrastructure operators/providers. On the other hand, end-user services refer to services provided to end users (e.g. content delivery, gaming etc) that in 5G environments require BH connectivity, referred to as BH services. The main technical innovations of the proposed solution include: i) an architectural framework aligned with the Software Defined Networking (SDN) open reference architecture [6] and the ETSI Network Function Virtualization (NFV) standard to jointly support FH and BH services as well as the adoption of flexible functional split options. This is a key innovation of the proposed architecture compared to contemporary LTE-A systems where FH and BH services are supported by separate and dedicated networks, while network control and management is closed, ii) a novel data plane design that converges heterogeneous wireless and optical solutions and, iii) a novel modelling framework adopting multi-objective optimization (MOP) techniques to evaluate the proposed architectural approach. This modelling framework focuses on optimal FH and BH service provisioning, with the overall objective to maximize the infrastructure energy efficiency and, minimize end-to-end service delays.

II. OVERVIEW OF THE 5G-XHAUL ARCHITECTURE

A. *Data Plane Architecture*

The 5G-XHaul data-plane design considers converged optical and wireless network domains in a common 5G infrastructure supporting both transport and access. In the wireless domain, a dense layer of small cells can be wirelessly backhauled through mm-Wave and sub-6 technologies. Alternatively, small cells can be connected to a CU through the 5G-Xhaul optical network. This adopts a hybrid approach combining a dynamic and elastic frame based optical network solution with enhanced capacity WDM PONs [7], to support the increased transport requirements of 5G environments in terms of granularity, capacity and flexibility.

Given that 5G-XHaul proposes the adoption of C-RAN to overcome traditional RAN limitations (Figure 1), it introduces the need to support new operational network services (FH) over the transport network. These emerge from the need to connect densely distributed RUs with the CU, meeting very tight latency and synchronization requirements. To maximize coordination and resource sharing gains 5G-XHaul proposes to support BH and FH jointly in a common infrastructure. Thus achieving improved efficiency and management simplification leading to measurable benefits in terms of cost, scalability and sustainability. Aiming to address the C-RAN challenges described above, 5G-XHaul proposes the adoption of flexible split options that can relax the tight transport requirements in terms of capacity, delay and synchronization. Figure 2 shows the range of “optimal split” options, that span between the “traditional distributed RAN” case, where “all processing is performed locally at the AP”, to the “fully-centralized C-RAN” case, where “all processing is allocated at the CU”. All other options allow allocating some processing functions at the RU, while the remaining processing functions are performed remotely at the CU. The optimal allocation of processing functions to be executed locally or remotely i.e. the optimal “split”, can be decided based on factors such as transport network characteristics, network topology and scale as well as type and volume of services.

A key enabler of the 5G-XHaul data plane (Figure 1) is the hybrid (passive-active) optical network transport that supports jointly FH and BH services offering the required connectivity, capacity and flexibility. The passive solution employs WDM-PONs, while the active solution adopts the highly versatile Time-Shared Optical Network (TSON) [7] extended to support novel features offering fine bandwidth granularity (variable length optical frames) and elastic bandwidth allocation capabilities.

Given the technology heterogeneity supported by the 5G-XHaul data plane, a critical function of the converged infrastructure is interfacing between technology domains. Interfaces are responsible for handling protocol adaptation as well as mapping and aggregation/de-aggregation of traffic across domains. Different domains (wireless/optical) may adopt different protocol implementations and provide very diverse levels of capacity (Mbps for the wireless domain to tens of Gbps for TSON), granularity (Kbps for the wireless domain to 100 Mbps for TSON) etc. A key challenge also addressed by these interfaces is mapping of different QoS classes across different domains as well as flexible scheduling enabling QoS differentiation mechanisms. More specifically, at the optical network ingress point (e.g. TSON edge node) the interfaces receive traffic frames generated by fixed and mobile users and arrange them to different buffers. The incoming traffic is aggregated into optical frames and is assigned to suitable time-slots and wavelengths according to the adopted queuing policy, before transmission in the TSON domain. For FH traffic a modified version of the CPRI protocol supporting the concept of functional splits (eCPRI) has been adopted. Note that due to the large variety of technologies involved in 5G, these interfaces need to support a wide range of protocols and technology solutions and execute traffic forwarding decisions at wire-speed. This requires the development of programmable network interfaces combining hardware level performance with software flexibility. The reverse function is performed at the egress TSON edge node. More information regarding interfacing of wireless and optical domains is available at [7], [13].

B. *Overarching Layered Architecture*

Managing and operating heterogeneous infrastructures integrating a variety of optical and wireless technologies and domains such as the 5G-XHaul infrastructure presents several challenges. To address these we propose the adoption of the integrated SDN/NFV paradigm. This will take advantage of the separation of control and data plane offered by SDN and the depoyments of the variety of NFV elements. Through this integration the benefits of the control and the holistic network view of SDN will be combined with the flexibility to provision services by composing Service Chains (SCs) through orchestrated network functions. SDN/NFV integration allows SDN controllers to control the Virtual Network Functions (VNFs) [11] enabling on-demand resource allocation for dynamically changing workloads [6]. SDN network elements may correspond to both Physical Network Functions (PNFs) and VNFs if they are implemented in virtualized environments, as software running on general-purpose hardware platforms [6]. The virtualization of network elements enables flexible allocation of data plane resources according to network applications requirements. On the other hand, SCs offering orchestrated service provisioning over heterogeneous environments are considered to be a possible network application, which can include SDN controller functions or interact with SDN controllers to provide VNFs.

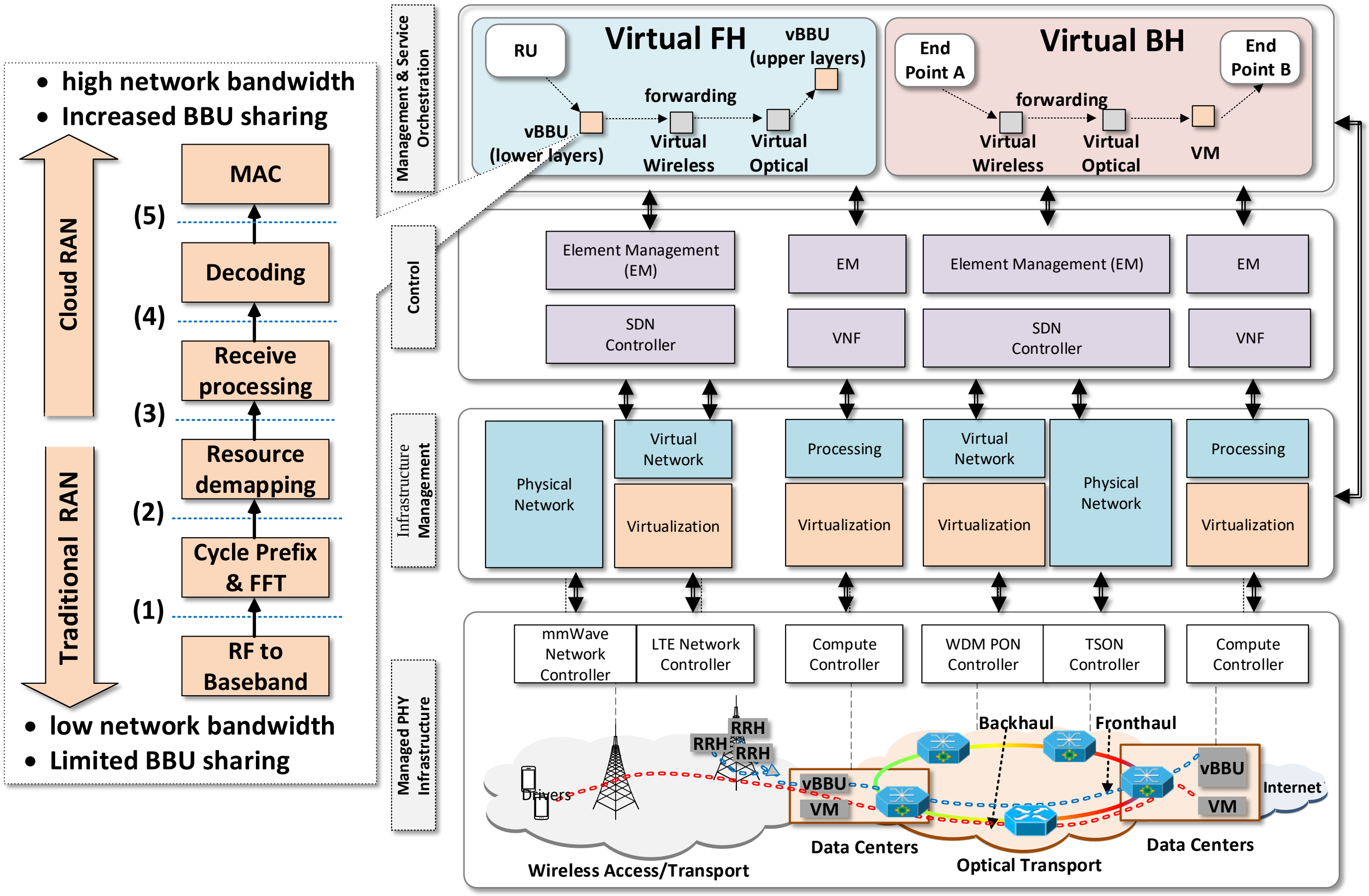


Figure 2: The overall overarching architecture supporting functional split processing [3]-[4].

The details of the 5G-XHaul overarching architecture adopting the integrated SDN/NFV paradigm to facilitate management and operation of the heterogeneous physical infrastructure (PI) are illustrated in Figure 2.

The Infrastructure Management Layer (IML) manages the different technology domains. This layer is responsible to enable multi-tenant operation through cross-domain slicing and virtualization facilitating joint FH and BH services over the common infrastructure. Information retrieval and communication between domains is handled by network and compute controllers located at this layer, enabling resource abstraction and virtualization. Therefore, IML supports traditional management of the PI together with advanced features required for virtualization and virtual resource management functions.

The Control Layer (CL) is responsible for cross-domain orchestration of virtual and PIs, created and exposed by the IML having an overall view of all network domains. CL provides end-to-end connectivity services in the form of SCs deploying converged control and management procedures with guaranteed QoS. CL supports configuration of both virtualized and non-virtualized heterogeneous resources as well as legacy devices, through a set of distributed SDN controllers and facilitates the development of enhanced VNFs to operate the 5G infrastructure seamlessly.

The Management and Service Orchestration Layer (MSOL) handles orchestration requirements for the delivery of network and compute services as well as composition and provisioning of SCs in multi-tenant environments deploying VNFs. MSOL is also responsible to support interoperability with legacy software and hardware.

III. USE CASE: JOINT OPTIMIZATION OF FH/BH

As already discussed the 5G-XHaul data plane architecture can jointly support FH and BH services adopting a hybrid optical transport, integrating passive and active optical networks. The higher layers of the architecture that facilitate access and management of both network and compute resources also play a key role. The ability of the IML to create virtual infrastructure (VI) slices across heterogeneous domains and to expose these to the upper layers is an instrumental architectural tool, facilitating the delivery of FH and BH services. Identifying optimal VIs in terms of both topology and resources includes:

- Ordering, referred to as SC, of the relevant functions (VNF or PNF) that need to be applied to the traffic flows traversing the VIs.
- Estimating the virtual resources required to support SC and executing the corresponding applications over the PI.
- Mapping of the virtual resources to the physical resources.

This process is shown at Figure 2, upper part. In this example two VIs, corresponding to different tenants, are able to support independently FH and BH functions over a common infrastructure.

In 5G-XHaul we assume a multi-technology transport network interconnecting RUs and end-users with a set of general-purpose servers hosted by the CU (as showcased e.g. by Alcatel-Lucent, Intel, China Mobile and Telefónica, Mobile World Congress 2015). To support virtual FH (VFH) services, over the 5G-XHaul infrastructure, RU demands are forwarded to a shared CU, hosting a set of sliceable and virtualised servers for processing. Compute resources are responsible for executing the various BB functions in a predefined order (left part of Figure 2). Based on the split option adopted, these functions can be partly executed locally at the RU or centrally at the CU. The split choice dictates the processing allocation, to local and central compute resources, and enforces the corresponding SC graph. A graphical representation of a typical virtual BH (VBH) service that supports content delivery (CDN) to end-users is shown in Figure 2. The SC graph indicates that the VBH service allows mobile traffic, generated at the wireless access domain, to traverse a hybrid multi-hop wireless/optical transport network, before it reaches the compute resources.

To evaluate the performance of this type of infrastructure and the proposed architecture, we have developed a mathematical framework, based on MOP, for the integrated wireless and optical network domains, considering the data plane described in Section II.A and the details of the compute resources required. Our study focuses on optimal planning of VFH and VBH infrastructures, in terms of both topology and resources considering overall power consumption and end-to-end delays. To identify the best performing FH and BH VIs, detailed power consumption and end-to-end delay models are considered. These models describe the details of the optical and wireless network as well as the compute domains and the associated interfaces, [9]. The results obtained, focus on the specific use case of joint FH and BH optimisation, assuming delivery of CDN services to the end-users.

The joint VFH/VBH design problem considers also a set of constraints ensuring efficient and stable operation of the planned Vis, summarized below:

- VFH and VBH infrastructures have specific requirements. In response to this, different VNFs are grouped and orchestrated in the form of SCs with specific processing and network requirements. To realize an SC, sufficient network and processing capacity must be allocated to the planned VIs for the interconnection and deployment of VNFs. The order of VNF processing is defined by the corresponding SC.
- Reservation of physical resources to support SC depends on the users' mobility model assumed, the size of the wireless cells and the traffic model adopted. Ideally, 100% overprovisioning of both network and compute resources across neighboring cells can guarantee seamless handovers. However, to improve resource efficiency the reservation of resources, residing in adjacent cells, can be linked to handoff probability. The amount of resources leased in the wireless domain is assumed to be an increasing function of the handoff probability [12]. Given that both the RUs and the end-users need to be supported by remotely located compute resources, the additional resource requirements also propagate in the transport network and the compute domain.
- The VI planning process considers a number of functions across different domains including flow conservation, mapping, aggregation and deaggregation of traffic.
- Given that both FH and BH services require compute processing the associated impact in the overall infrastructure evaluation is considered. Therefore, the traffic associated with these services is

mapped, not only to network resources, but also to compute resource requirements. This introduces an additional constraint, linked with the conversion of network-to-compute resource requests. To achieve this, a mapping parameter, defined as “network-to-compute” parameter, is introduced providing the ratio of network requirements (in Mbps) and computational requirements (in Operations Per Second (OPS)), of a specific service demand. This parameter takes low values, for cloud services requiring high network bandwidth and low processing capacity (e.g. video streaming). On the other hand, it takes high values for tasks requiring intensive processing and low network bandwidth (e.g. data mining, Internet-of-Things). Regarding BH services, the Standard Performance Evaluation Corporation recently established the Cloud subcommittee to develop benchmarks able to measure these parameters. Taking a similar approach the authors in [14] measured the average ratio between computational and network bandwidth requirements for various “Big Data” analytics workloads. Similarly, FH services require specific computing resources to support BB processing. The processing power depends on the details of the BBU [3]-[4] including processing tasks related to Fast Fourier Transforms (FFT), error correction, processing-resource mapping/de-mapping etc. calculated in Giga OPS (GOPS). The resulting processing power depends on the LTE system configuration [4].

- Our analysis takes into consideration end-to-end delays for specific services e.g. FH or real time BH services. In highly loaded heterogeneous networks, such as the 5G-XHaul solution, end-to-end delay can be greatly influenced by queuing delays associated with the interfaces across the infrastructure domains. In this context, the choice of suitable queuing and scheduling policies at the interfaces offers significant delay benefits. Traditionally, these systems can be mathematically modeled applying queuing theory and open/closed mixed queuing networks. However, such a model is not able to abide to the strict FH latency constraints. To address this issue, the queuing delays for the VFH are modeled under worst case operational conditions, using network calculus theory [13].
- Flexible processing splits refer to the choice of a single split option for every time instance. Once the split option has been selected, the corresponding SC is applied across the network, deploying specific network and compute resources as dictated by the relevant split. [3], [4].

Depending on the functional split, some of the processing is performed by compute resources either at a local cloudlet [12] $c, c\epsilon\mathcal{C}$ ($\mathcal{C}$ denotes the set of cloudlets) with cost w_c per GOPS or at a remote regional DC $s\epsilon\mathcal{S}$ ($\mathcal{S}$ denotes the set of DCs) with cost w_s per GOPS. Assuming that the cost for operating FH capacity $u_{FH,e}$ of physical link $e\epsilon\mathcal{E}$ ($\mathcal{E}$: set of physical links) is w_e and $\pi_{FH,s}$ $\pi_{FH,c}$ are the BBU processing capacities at the remote server and the cloudlet, respectively, the optimal VFH infrastructure is determined by minimizing the following cost:

$$min\,\mathcal{VFH}(\boldsymbol{u},\boldsymbol{\pi}) = \sum\nolimits_{e\epsilon\mathcal{E}} w_e\, u_{FH,e} + \sum\nolimits_{s\epsilon\mathcal{S}} w_s \pi_{FH,s} + \sum\nolimits_{c\epsilon\mathcal{C}} w_c\, \pi_{FH,c} \quad (1)$$

subject to the constraints described above.

As the optical transport requires very small amount of power to operate, higher pooling gains are expected when C-RAN solutions are adopted compared to traditional RANs. The impact of centralization is expressed through transport network overloading introduced by FH services, leaving limited resources for BH services. In view of this we set a secondary optimization objective with the aim to minimize BH end-to-end delay, subject to demand processing and capacity constraints:

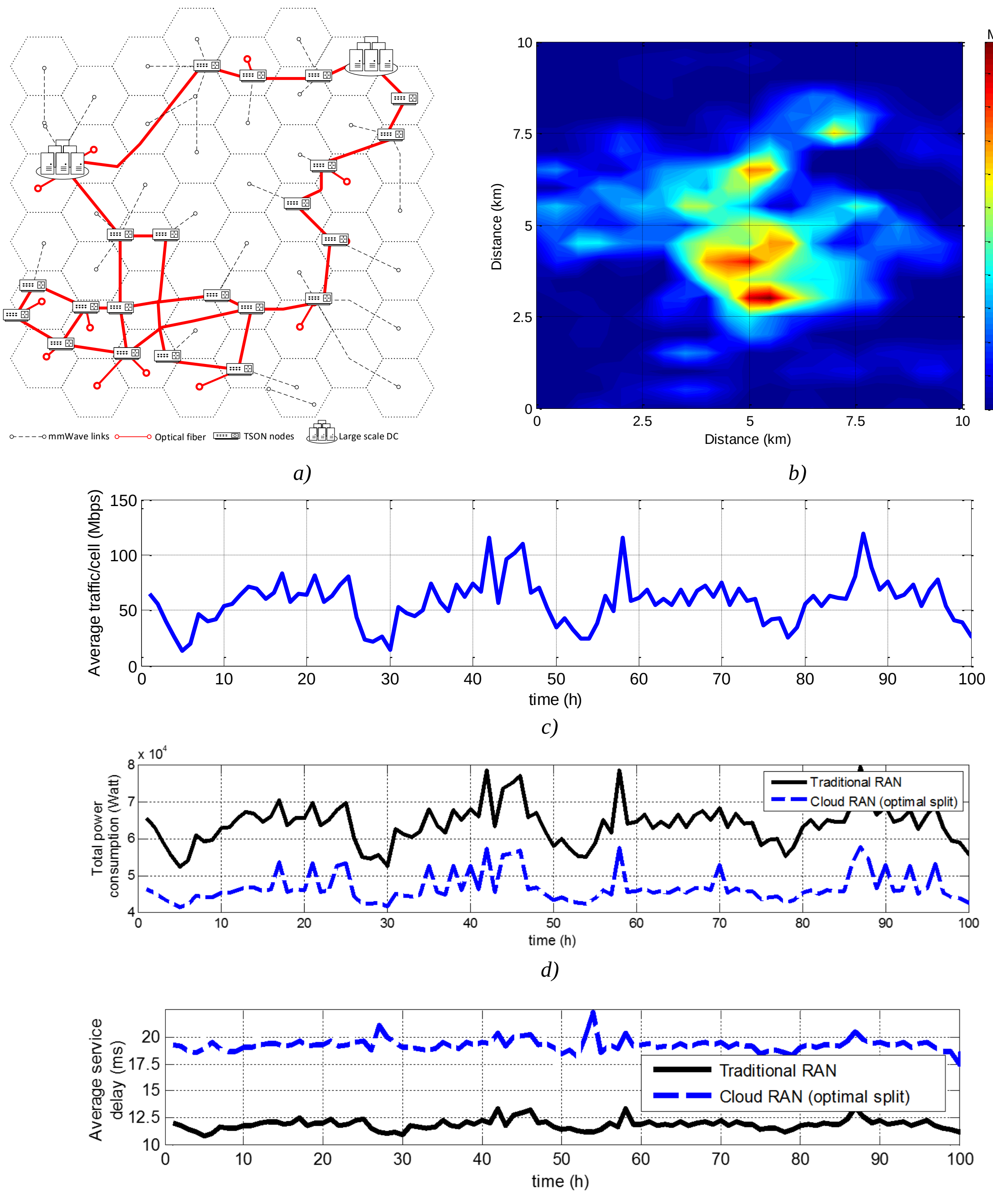
$$\min \mathcal{VBH}(\mathrm{u},\pi) = \sum\nolimits_{\mathrm{e}\epsilon\mathcal{E}} \frac{1}{\mathcal{U}_{\mathrm{e}} - \mathrm{u}_{\mathrm{FH,e}} - \mathrm{u}_{\mathrm{BH,e}}} + \sum\nolimits_{\mathrm{s}\epsilon\mathcal{S}} \frac{1}{\Pi_s - \pi_{FH,s} - \pi_{BH,s}} + \sum\nolimits_{\mathrm{c}\epsilon\mathcal{C}} \frac{1}{\Pi_c - \pi_{FH,c} - \pi_{BH,c}} \quad (2)$$

where $u_{BH,e}$, $\pi_{BH,s}$ represent the BH related network and server capacity, respectively, $\mathcal{U}_e$, is the total capacity of e and Π_s, Π_c are the total processing capacity of the DC s and the cloudlet c, respectively.

The MOP described through (1)-(2) can be written as $\min \mathcal{F}\,(\boldsymbol{u},\boldsymbol{\pi}) = [\mathcal{VFH}(\boldsymbol{u},\boldsymbol{\pi}),\quad \mathcal{VBH}(\boldsymbol{u},\boldsymbol{\pi})]$ subject to the previously discussed constraints. This problem is then transformed from an MOP into a single objective problem using the Pascoletti-Serafini scalarization technique [10] and solved using Lagrangian Relaxation. In the following section, the performance of the overall architecture is evaluated in terms of power consumption and service delay adopting a realistic network topology and actual traffic statistics [15].

IV. PERFORMANCE EVALUATION

The network topology assumed is the Bristol 5G city infrastructure (Figure 3 (a)). In this infrastructure a set of 50 APs are evenly distributed across a 10x10 km^2 area. APs are backhauled through microwave point-to-point links and TSON is adopted for the optical transport. TSON deploys a single fiber per link, 4 wavelengths of 10Gbps each per fiber and minimum bandwidth granularity of 100Mbps. In the present study, w_e is associated with the power consumption of link $e\epsilon\mathcal{E}$. Power consumption figures for TSON can be found in [7], [13]. The microwave transceivers considered, have 2Gbps bandwidth and their power consumption is 45W (Huawei OptiXRTN310).



a) *b)*

c)

d)

e)

Figure 3 a) Bristol 5G city network topology with mmWave backhauling, b) Snapshot of spatial traffic load and c) averagetraffic/BS based on the dataset[10]during 8/2012, d)-e) Total power consumption and total service delay over time for the traditional RAN.

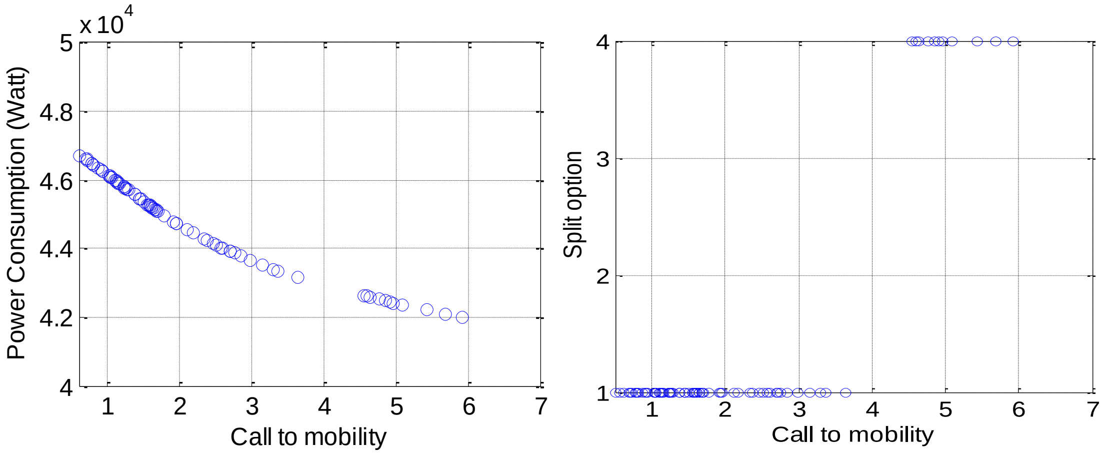
Furthermore, a 2×2 MIMO scheme with adaptive number of transmission elements, carrier frequency 2.6GHz, 20 MHz bandwidth adjustment and capacity per cell up to 201.6 Mbps has been considered. Mobile users are distributed and generate traffic over the serviced area according to real datasets reported in [15] (Figure 3 b). The following two scenarios are studied:

a) "*Traditional RAN,*" where power consumption per AP ranges between 600 and 1200 Watts under idle and full load conditions, respectively, and commodity servers are used to support CDN services.

b) *"C-RAN with virtual BBUs (vBBUs)"* where commodity servers are used to support both FH (through the creation of vBBUs [1]) and BH CDN services.

For *C-RAN with vBBUs*, where optimal split options are deployed, two types of servers have been considered: a) small scale commodity servers (cloudlets) close to the APs and, b) commodity servers hosted by large scale DCs (Figure 3 (a)) with an average cost equal to 2Watts/GOPS and 1.6Watts/GOPS, respectively. Details regarding the numerical values used in the simulations are provided in [7]. Although both types of servers can provide the necessary processing power for C-RAN and CDN services, large scale DCs provide superior performance per Watt, compared to cloudlets. Figure 3 (d) shows that significant energy savings (ranging between 60-75%) can be achieved adopting the C-RAN approach using the integrated wireless-optical infrastructure, compared to traditional RAN. However, due to sharing of network resources between BH services and high priority FH services, C-RAN leads in increased BH service delays that remain below 25 ms (Figure 3 (e)). On the other hand, traditional RAN provides minimum end-to-end BH service delays, as no sharing with FH services is required, but at the expense of increased power consumption due to the limited BBU sharing.

The impact of mobility on the total power consumption and the optimal split option adopted is shown in Figure 4 (a) and (b), respectively. The call-to-mobility factor is defined as the ratio of the service holding time over the cell residence time [13], with low call-to-mobility factor values indicating high degree of mobility. It is known that high degree of mobility introduces additional resource requirements in the wireless domain. To ensure seamless end-to-end connectivity between end-users, RUs and compute resources, these additional resource requirements also propagate across the transport network and the compute domains. In Figure 4 (b) it is observed that lower split options are beneficial for higher mobility, enabling a larger number of BB processing tasks to be offloaded to remote DCs. Given that BB processing requirements increase with mobility, a higher degree of centralization benefits the system, due to increased consolidation and improved performance per watt that large scale remote DCs offer, compared to local cloudlets.

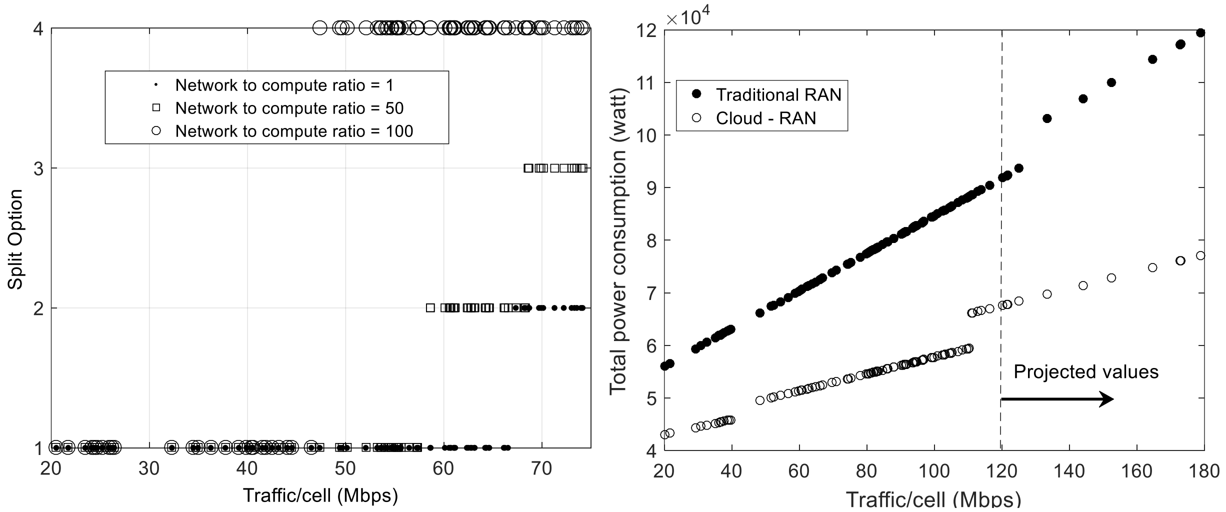


a)

b)

Figure 4: Impact of mobility on a) power consumption and b) optimal split option (load 18Mbps/cell).

Figure 5 (a) illustrates the impact of service requirements in terms of network and compute resources on the optimal split option adopted. CDN services with high network-to-compute ratios (e.g. video analytics) require significant network resources to operate, leading to overutilization of transport capacity. This effect is counter-balanced by the selection of higher split options (i.e. options 3, 4) that require lower bandwidth for the interconnection of RUs with CUs compared to the bandwidth requirements of lower split options (i.e. options 1, 2). The impact of the traffic load on the total power consumption is illustrated in Figure 5 (b). As expected, for higher traffic load, the total power consumption increases, and a step-like increase is observed, above 45 Mbps per cell traffic load. Beyond this threshold, the preferable system split option becomes split 4 (rather than split 1) and a large number of cloudlets per geographic region are activated to support BB processing requirements.



a)

b)

Figure 5 a) Split option as a function of load for different Compute to network ratios. b) Impact of the traffic load on the total power consumption

Finally, the impact of the relative processing and transport network cost, on the optimal split option, is illustrated in Figure 6. The relative local to remote processing cost, is defined as the ratio of the power consumed for data processing at the local cloudlet over the power consumed for processing of the same data remotely at large scale DCs. It is seen that increasing this ratio makes it beneficial to perform more processing functions at large scale remote DCs. Thus a lower split option is preferable. To include the impact of the network cost in this analysis, the end-to-end transmission cost is also plotted in Figure 6. As the transmission cost increases (higher number of wireless hops), it is beneficial to perform more processing functions at the local cloudlets and hence adopt a higher split option.

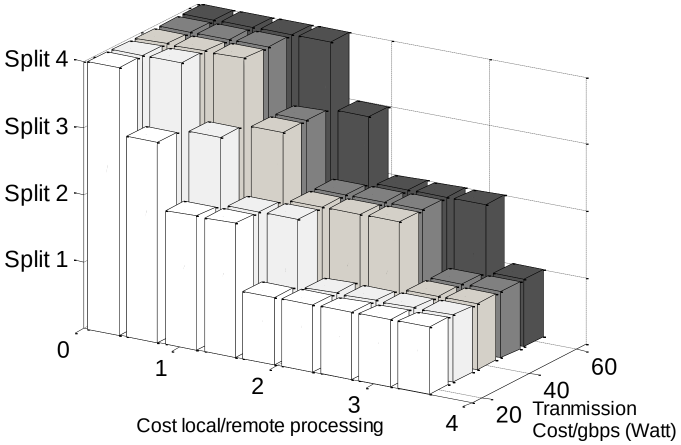


Figure 6 Split options for various processing and transmission costs.

V. CONCLUSIONS

This paper presents a converged optical-wireless 5G infrastructure proposed by the EU 5GPPP project 5G-XHaul aiming to support jointly operational network and end-user services. The overarching architecture proposed is aligned with the SDN reference architecture and the ETSI NFV standard. A novel MOP modeling framework has been developed to evaluate the performance of the 5G-XHaul architecture taking into consideration the joint support of FH and BH services. Our modeling results show that the proposed architecture can offer significant benefits in terms of energy consumption but at the expense of end-user service delays.

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Biographies

Anna Tzanakaki is an Assistant Professor at the National and Kapodistrian University of Athens, Greece and a Research Fellow at the University of Bristol, UK. She is a co-author of over 160 publications in international journals and conferences. Her research interests include converged networks, network architectures, technologies and protocols.

Markos Anastasopoulos holds a Diploma degree in Electrical and Computer Engineering, an MBA degree in financial engineering and a Dr. Eng. degree from the National Technical University of Athens. Currently, he is a researcher at the High Performance Networks Group of University of Bristol, UK working in the design of converged 5G infrastructures.

Ignacio Berberana Not available

Dimitris Syrivelis received his Bsc degree from Technical University of Crete and PhD from the University of Thessaly. He was a post-doctoral fellow at the Centre for Research and Technology Hellas. He is currently a research engineer at the IBM Research Dublin lab and works on Software Defined Infrastructures for Hyperscale computing.

Paris Flegkas received a Diploma in Electrical and Computer Engineering from the Aristotle University, Greece, an MSc and a PhD from the University of Surrey, UK. He is an adjunct Lecture and a Senior Researcher at the University of Thessaly, Greece. His research focuses on SDN, NFV Management and information-centric networking.

Thanasis Korakis is an Assistant Professor at the Department of Electrical and Computer Engineering at the University of Thessaly, Greece. He has published more than 60 papers and holds 5 patents. He was the PI for several NSF USA projects and has participated in several EU projects. He is the Associate Director of NITLab.

Daniel Camps-Mur is leading the Mobile and Wireless Internet group at I2CAT in Barcelona. Previously, he was a senior researcher at NEC Network Laboratories in Heidelberg, Germany. He holds a Masters degree and a Ph.D. from the Polytechnic University of Catalonia (UPC). His research interests include mobile networks and IoT.

Ilker Demirkol is a research professor in Department of Network Engineering at Universitat Politècnica de Catalunya. His research focus is on communication protocol development and evaluation for wireless networks. He has also held several positions in industry as network engineer, system and database consultant.

Jesús Gutiérrez Terán received the B.S. degree and the Ph.D. in Telecommunication Engineering from the University of Cantabria, in 2008 and 2013, respectively. Since 2013, he is with IHP in Frankfurt (Oder), Germany. His research interests include digital signal processing for high performance hardware architectures and Millimeter Wave systems.

Eckhard Grass received the Dr.-Ing. degree in Electronics from Humboldt-University in Berlin, in 1993. After six years of research and lecturing in London, UK, he is since 1999 with IHP, leading a research group on Wireless Broadband Communications. Furthermore, he is Professor at Humboldt-University Berlin since 2011.

Qing Wei received her MSc degree in Communication Engineering from TU Munich, Germany in 2001. From 2002, she worked as a researcher/senior researcher at DOCOMO Euro Labs. In 2015, she moved to Huawei Technologies, working as a principal researcher in the area of 5G mobile network architecture and network programmability.

Emmanouil Pateromichelakis received his MSc and PhD degree in Mobile Communications from University of Surrey, UK in 2009 and 2013 respectively. From 2013 till 2015 he was post-doctoral fellow at 5GIC, University of Surrey. He is currently working as Senior Researcher at Huawei Technologies, focusing on 5G and beyond solutions.

Nikola Vucic received his Dr.-Ing. degree from TU Berlin, Germany, in 2009. From 2003 until 2010, he was a research associate at Fraunhofer HHI, Berlin. Since 2011, he has been with Huawei Technologies in Munich, Germany, working as a senior researcher in the areas of wireless networks and future internet.

Albrecht Fehske received his PhD from Vodafone Chair, TU Dresden in 2014 with highest honors. He co-authored more than 40 research publications. In 2013, Albrecht co-founded the Airrays, a startup company, which delivers fully adaptive antenna technology for 4G and upcoming 5G radio access networks.

Michael Grieger received his PhD from Vodafone Chair, TU Dresden in 2014. He co-authored 36 research publications and is inventor of 4 patents. Today, Michael is with Airrays GmbH which he co-founded in 2013. Airrays delivers fully adaptive antenna technology for 4G and upcoming 5G radio access networks.

Michael Eiselt started his career in optical communications in 1989and has worked for various companies and research organizations in Germany and the USA. As a Director Advanced Technology at ADVA Optical Networking, Germany, he is currently leading physical layer research for high-speed long-haul, data-center interconnect and access applications.

Jens Bartelt received his Dipl.-Ing. (MSEE) from Technische Universität Dresden, Germany. He is a research associate at the Vodafone Chair Mobile Communications Systems at TU Dresden, Germany, working towards his Ph.D. He is involved in several 5G research activities, including the EU projects iJOIN, 5G-XHaul and the 5G Lab Germany at TU Dresden.

Gerhard P. Fettweis. Dipl.-Ing. and Ph.D. degrees, Aachen University of Technology, Germany. Since September 1994 he holds the Vodafone Chair at Technische Universität Dresden, Germany. In 2012, he received an Honorary Doctorate from Tampere University**.** He is a well-known entrepreneur who has co-founded 13 start-ups and coordinates 2 DFG centers at TU Dresden.

Dr. George Lyberopoulos has been involved in more than 30 EU and national research projects. Dr. Lyberopoulos joined COSMOTE in 1999, while today he is heading the Research & Development Dept., Fixed and Mobile. Dr. Lyberopoulos is author of over 50 scientific papers in the areas of mobile telecommunications.

Eleni Theodoropoulou, MSc., Telecom Engineer. She has been working for Greek Mobile Operators since 1994. She has participated in several EU and national research projects and authored several scientific papers in the area of mobile communications. Since 2009, she is heading the R&D Projects Mobile Section of COSMOTE.

Dimitra Simeonidou is a Professor at the University of Bristol, the Smart Internet Lab Director, Chief Scientific Officer of Bristol Is Open, Head of the High Performance Networks group and a Royal Society Wolfson scholar. She is a co-author of over 400 publications and 12 patents. Her research focuses on High Performance Networks, SDN and Smart City infrastructures.

Figures

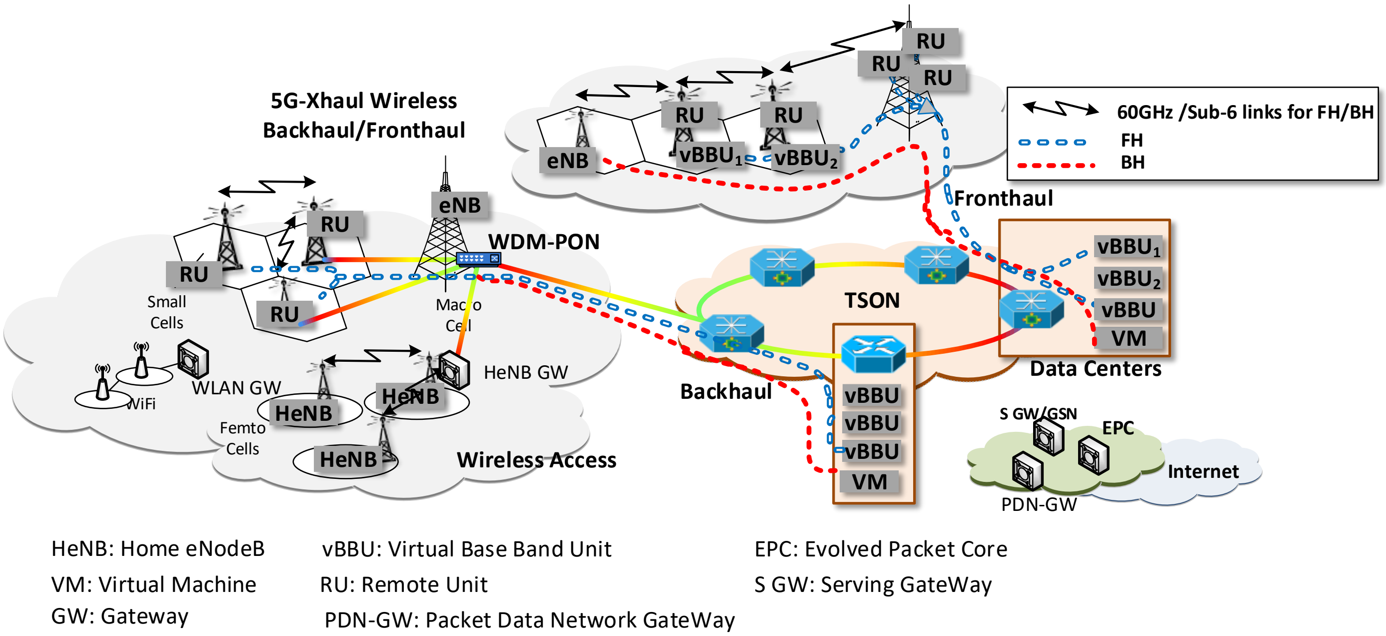


Figure 1:The 5G-XHaul Physical Infrastructure: FH and BH services are provided over a common wired/wireless network infrastructure. In the FH case, parts of the BBU processing can be performed locally and some parts remotely at the DCs enabling the C-RAN flexible split paradigm. BBUs are executed in general purpose servers in the form of virtual entities. BH services interconnect end-users with Virtual Machines hosted in the DCs.

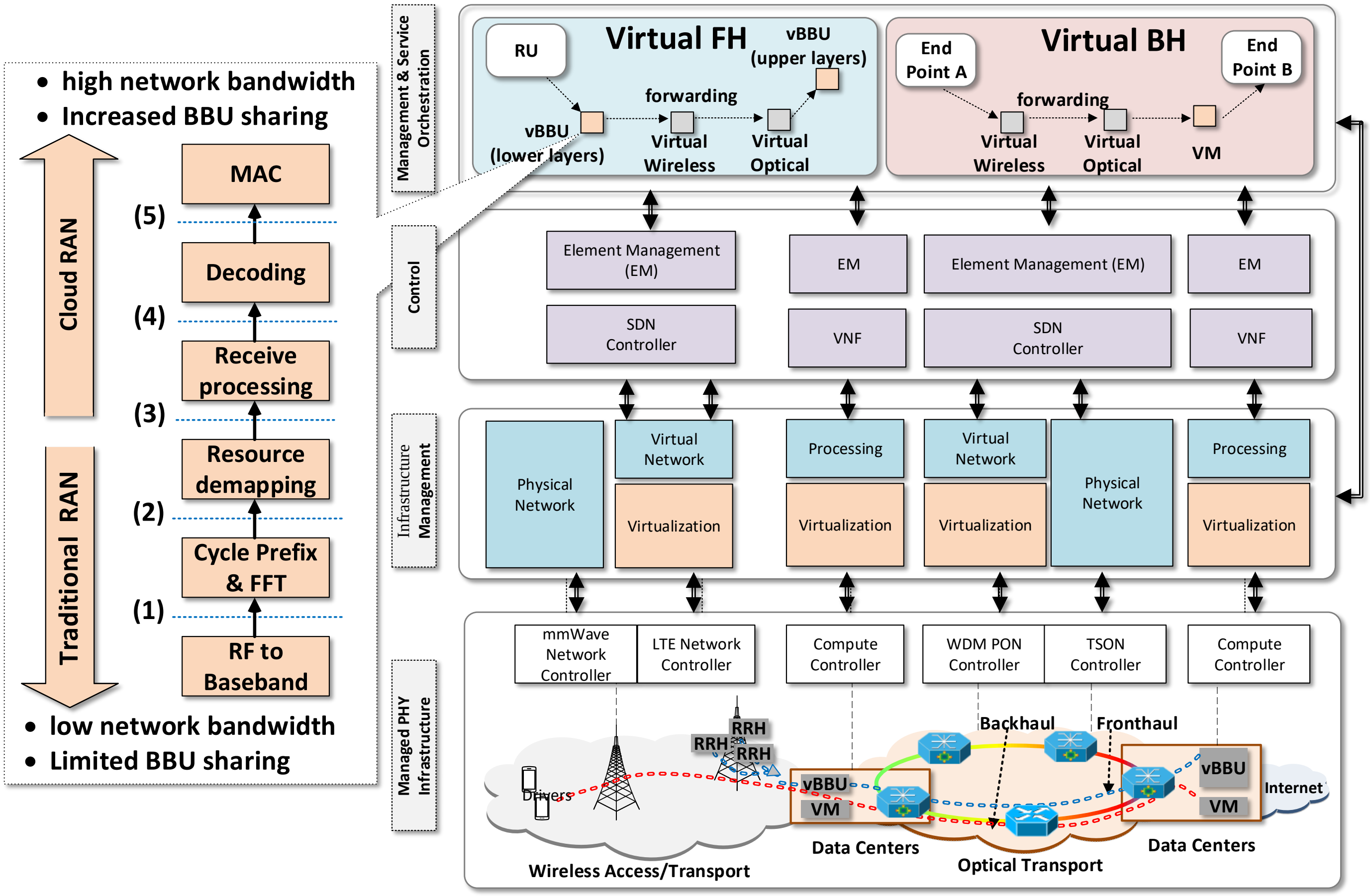


Figure 2: The overall overarching architecture supporting functional split processing [3]-[4].

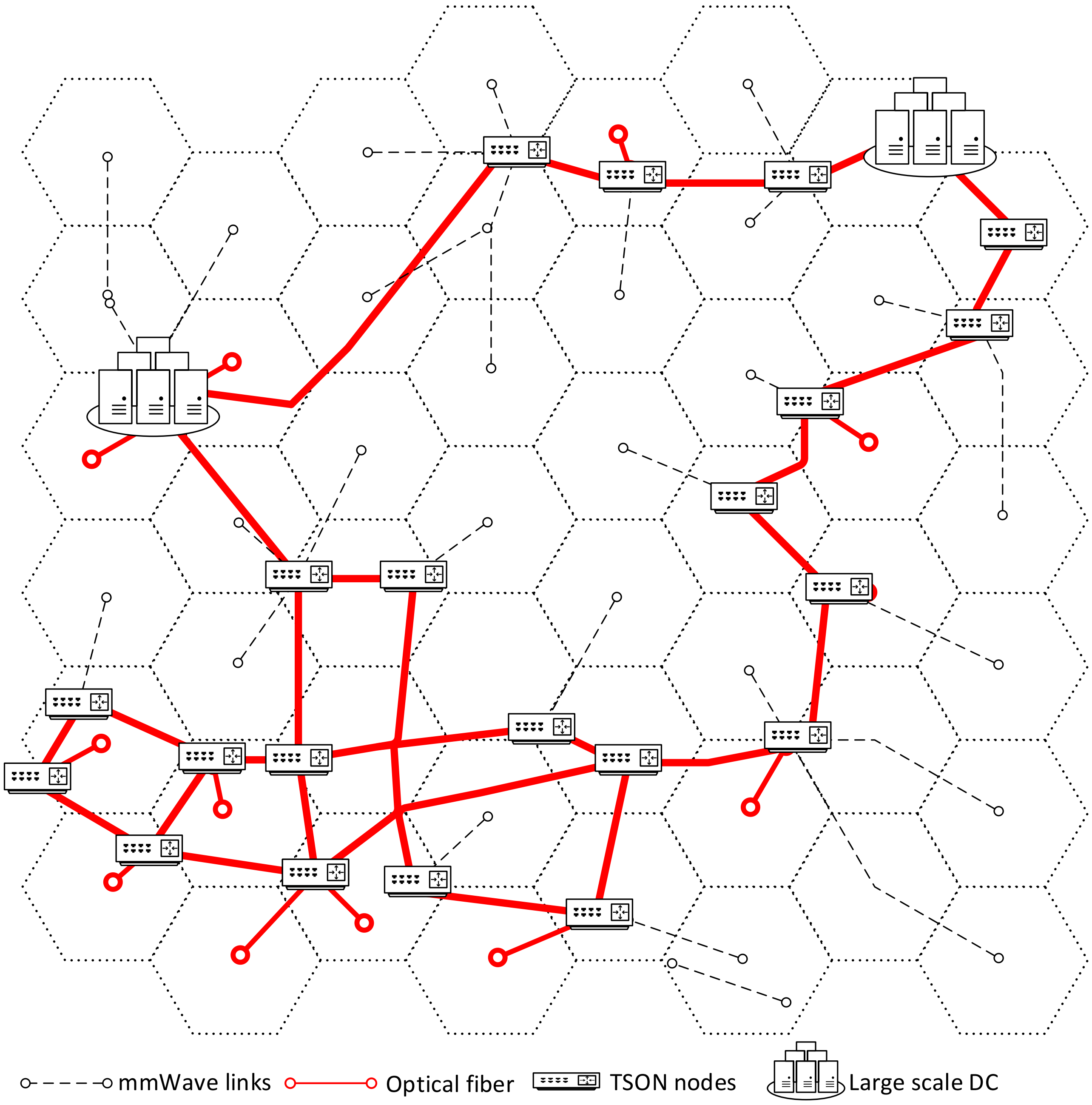


Figure 3 a)

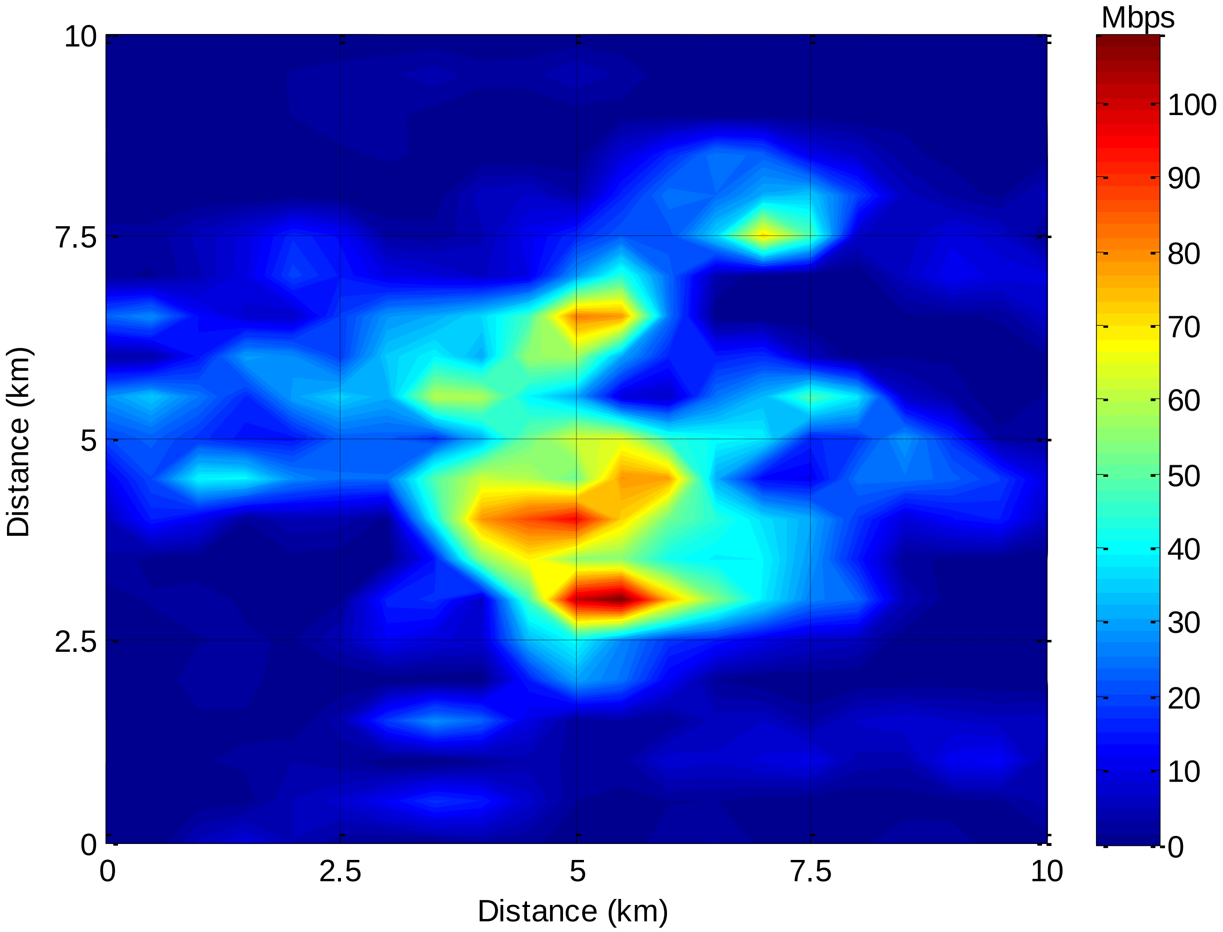

Mbps
10
7.5
5
2.5
0
0
2.5
5
7.5
10
Distance (km)
Distance (km)
100
90
80
70
60
50
40
30
20
10
0

Figure 3 b)

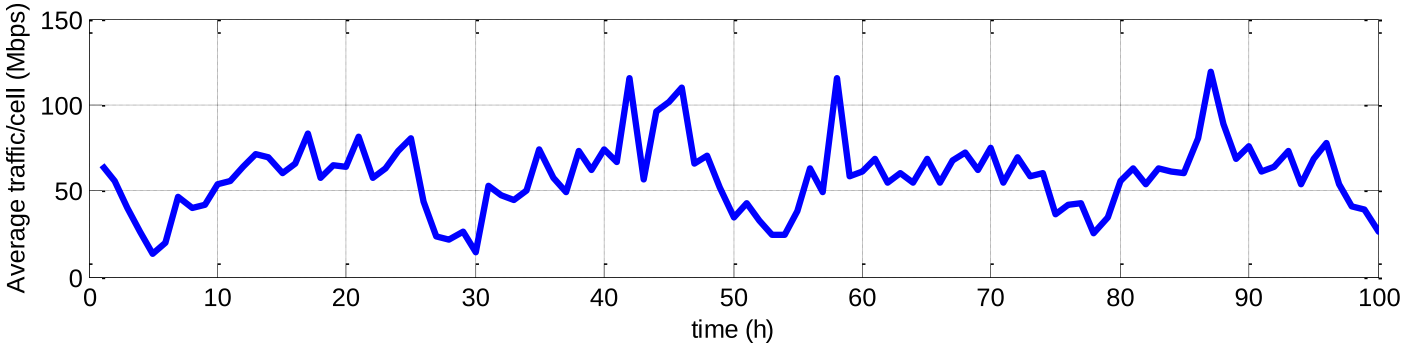

Average traffic/cell (Mbps)
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
time (h)

Figure 3 c)

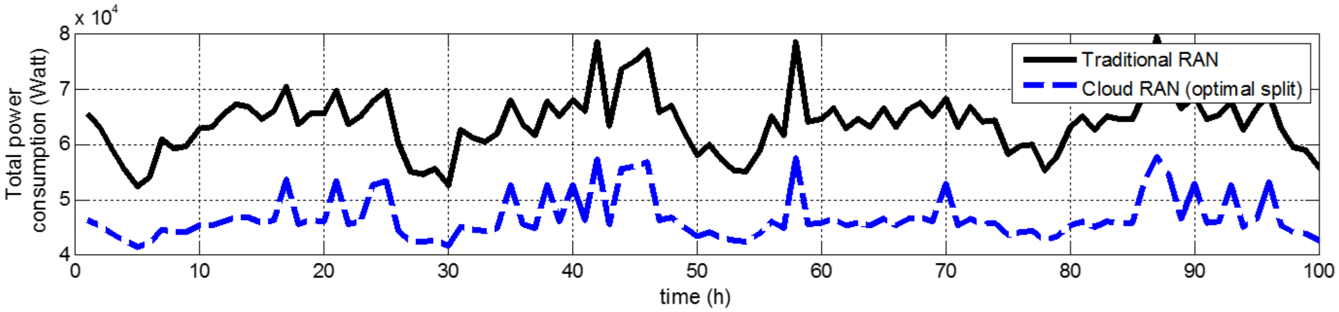
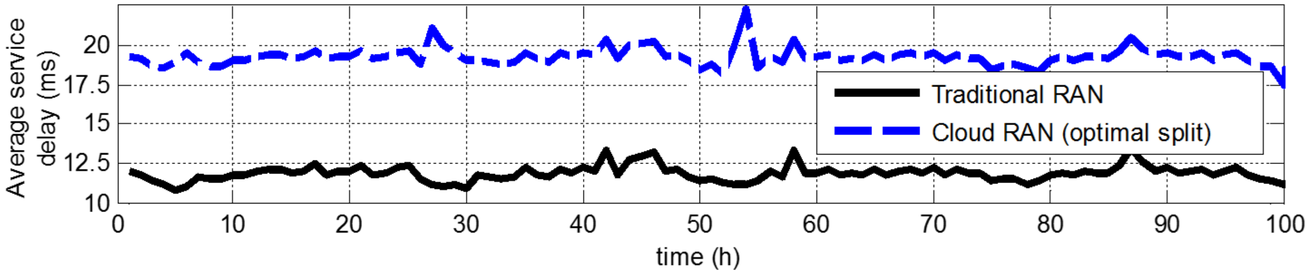

x 10^4
8
7
6
5
4
Total power consumption (Watt)
0
10
20
30
40
50
60
70
80
90
100
time (h)
Traditional RAN
Cloud RAN (optimal split)

Figure 3 d)



e)

Figure 3 a) Bristol 5G city network topology with mmWave backhauling, b) Snapshot of spatial traffic load and c) averagetraffic/BS based on the dataset[10]during 8/2012, d)-e) Total power consumption and total service delay over time for the traditional RAN.

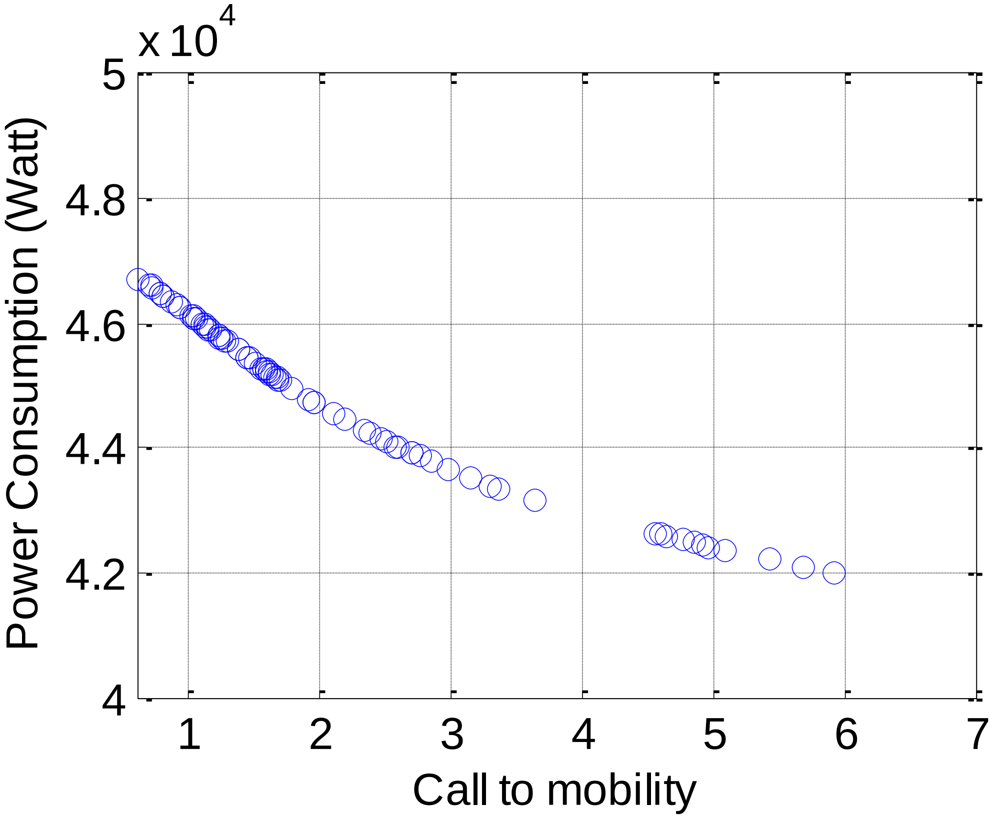

x 10^4
5
4.8
4.6
4.4
4.2
4
Power Consumption (Watt)
1
2
3
4
5
6
7
Call to mobility

Figure 4 a)

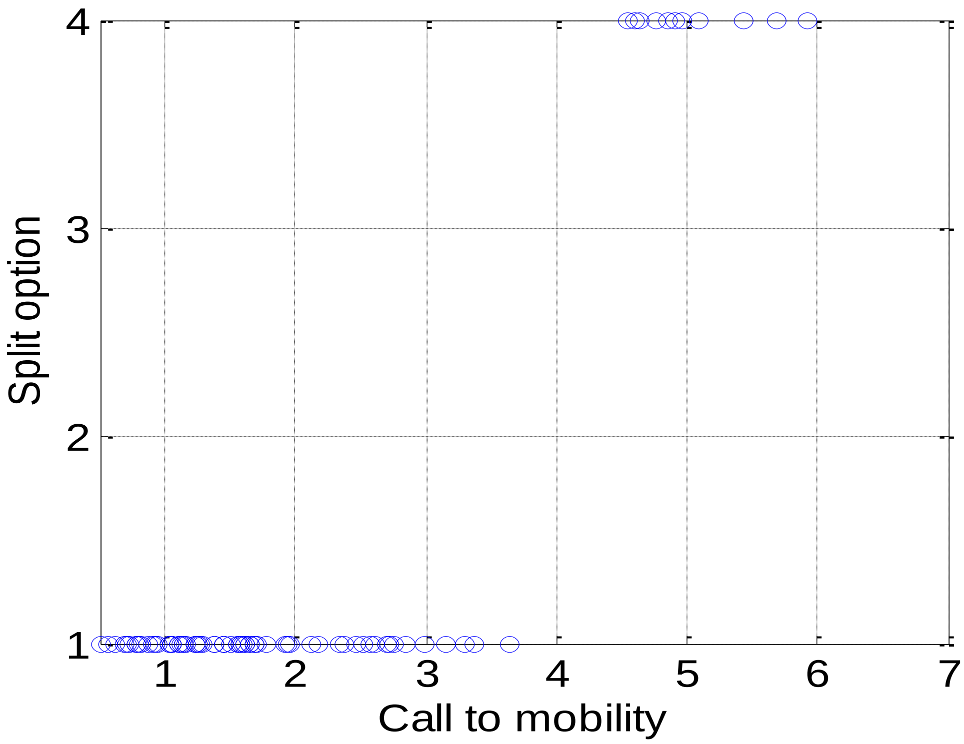


Figure 4 b)

Figure 4: Impact of mobility on a) power consumption and b) optimal split option (load 18Mbps/cell).

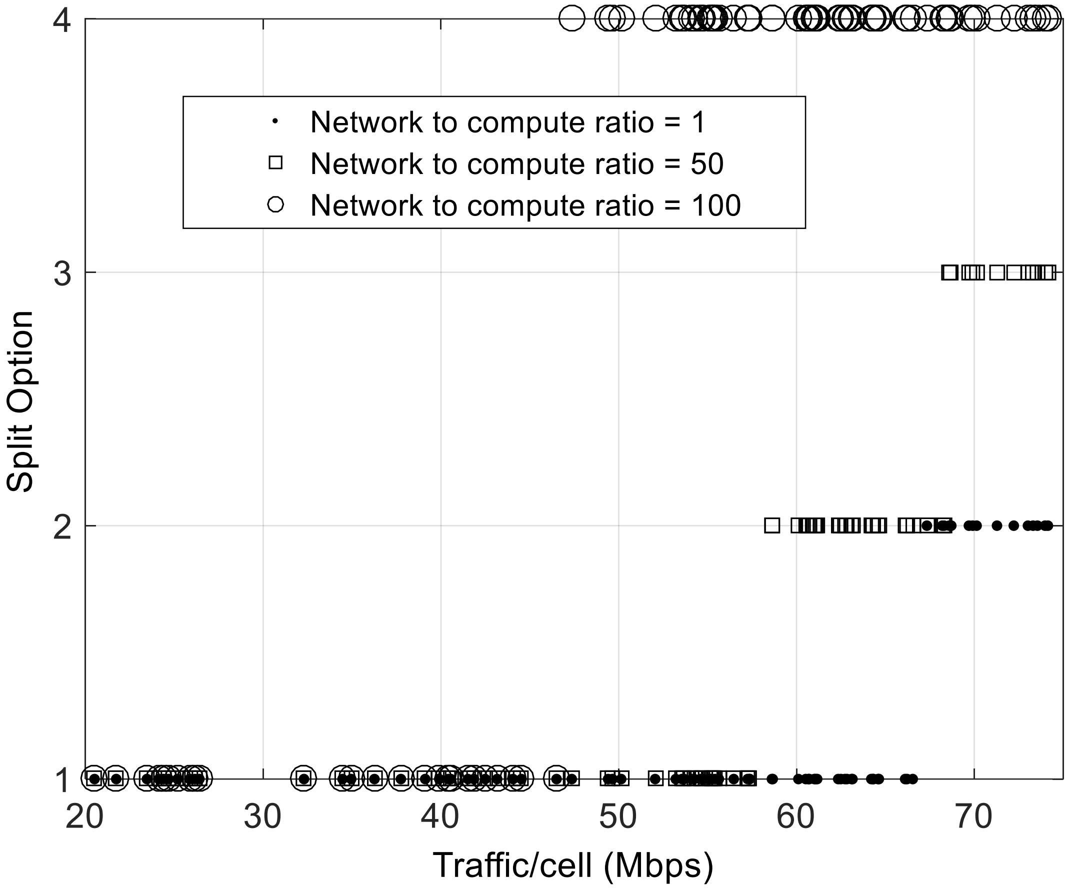

4
3
2
1
20
30
40
50
60
70
Split Option
Traffic/cell (Mbps)
Network to compute ratio = 1
Network to compute ratio = 50
Network to compute ratio = 100

Figure 5 a)

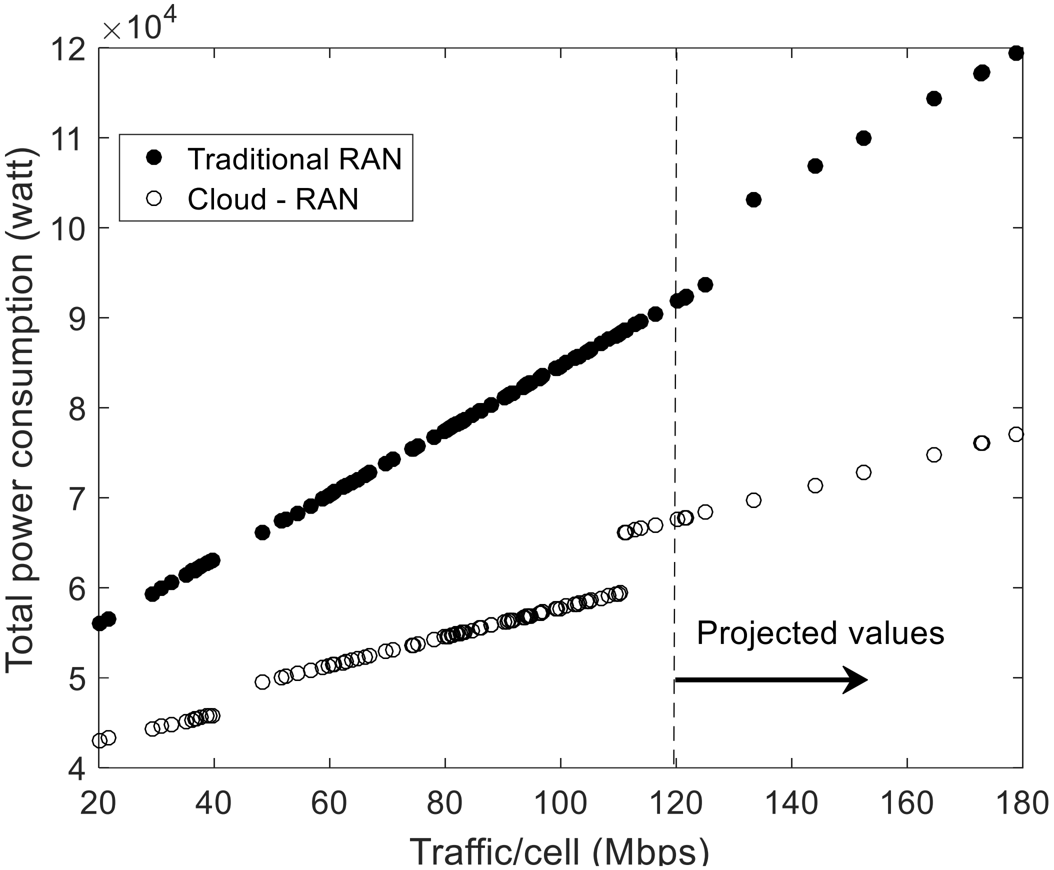


Figure 5b)

Figure 5 a) Split option as a function of load for different Compute to network ratios. b) Impact of the traffic load on the total power consumption

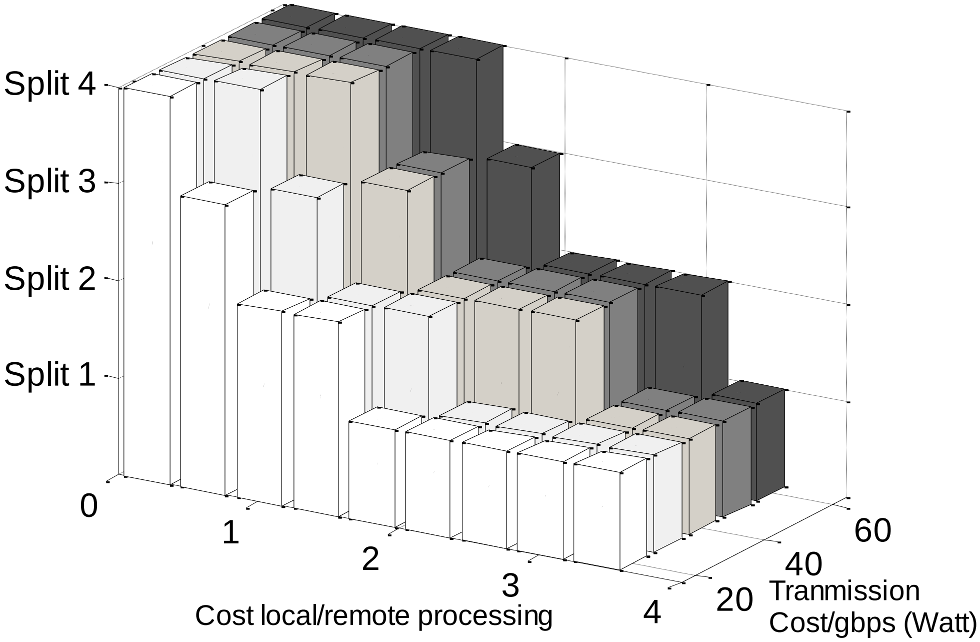


Figure 6 Split options for various processing and transmission costs.