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Poster Paper

Challenges of Designing Jointly the Backhaul and Radio Access Network in a Cloud-based Mobile Network

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Abstract: In this work, we give an overview of the main challenges that must be tackled to perform a joint design of the backhaul and radio access network in a cloud-based mobile network. The deployment of a very dense network based on small cells connected through a heterogeneous backhaul is a realistic way of achieving a high throughput in a mobile network. But, the non-ideal characteristics of this backhaul and the blurring borders between access and the backhaul networks require a joint design of both, involving the three lower OSI layers. In the physical layer, we consider to use adaptable techniques including In-Network-Processing (INP) and Multi-Point Turbo Detection, as well as Coordinated Beamforming and Joint Network-Channel Coding. Regarding the MAC layer, we pay special attention to partly distributed algorithms operating on smaller time-scales that take into account backhaul constraints and inter-cell interference. Finally, in the network layer we propose the use of cooperative routing schemes that optimize the cell load distribution and admission and congestion control algorithms that use access and backhaul information. Based on these approaches, a joint design of access and backhaul network can be effectively carried out, in order to enable the deployment of small-cells and heterogeneous backhaul.

Keywords: small-cell networks, small-cell backhauling, RAN-as-a-Service, cloud-infrastructure, backhaul/access co-design.

1. Introduction

Future mobile networks need to cope with exceptionally greater traffic volumes, with disparate data rates ranging from machine to machine (M2M) communications (low data rates) to HD video (high data rates). There are several main drivers of this traffic volume increase, among which we can highlight the following: *i)* the number of mobile Internet users grows exponentially: the percentage of EU residents who access the Internet through a mobile device has increased from less than 2% in 2006 to almost 8% in 2010, and M2M communications are becoming quite relevant; *ii)* Internet content becomes more data-rich over the years and features more multimedia content today: during the last five years the average size of websites has tripled and video content accounts for more than 40% of overall mobile data traffic, with Cisco forecasting that by 2015 this will increase to 66%; *iii)* mobile de-

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vices are used more frequently and for more diverse services: as an example, the number of mobile applications available on Apple store and Google Play is more than half a million and about 10,000 apps are added each month; *iv)* end-user devices become more powerful and have greater screen-resolution as more tablets and laptops are in use to access the mobile Internet: the percentage of the EU population that uses a laptop and a wireless access at home or work to access the Internet has doubled from less than 10% in 2007 to almost 20% in 2010.

This trend of exponentially increasing data volumes is confirmed by [1] which forecasts that traffic will double every year. This implies an increase of about 1000 times over the next 10 years. According to [2], per-user data rates are expected to grow by a factor of up to 50-100 and the density of mobile Internet users is expected to increase by a factor of up to 10. This implies a 1000-fold increase in demand by 2020. Hence, the throughput carried by a mobile network (system throughput) must grow correspondingly to sustain the data rate development that has been observed during recent decades. The Digital Agenda of the EC [3] reflects this development by setting a goal of providing data rates of at least 30 Mbit/s to all EU citizens by 2020 with 50% of them accessing the Internet with at least 100 Mbit/s. These goals cannot be achieved by adding fixed lines only. They require a significant extension of mobile access because more users are accessing the Internet solely through mobile networks.

Taking the 3GPP Long Term Evolution-Advanced (LTE-A) architecture as a baseline, we identify four measurable objectives that future mobile networks should meet: area throughput, energy-efficiency, cost-efficiency and utilization efficiency. The first one is to increase the system throughput within the same spectrum by a factor of 50-100. The second and third ones are to reduce energy-per-bit to less of 5% and to reduce the cost-per-bit to less than 10% of that of current systems. Finally, the last objective is to increase the utilization efficiency in relevant scenarios to more than 75%.

In order to meet these goals, we propose an enhanced mobile network architecture, based on the following key enablers and concepts: *i)* deployment of very small cells, as a way to provide better per-link quality and better reuse of the spectral resources; *ii)* centralized processing, in order to handle the increasing interference in very dense networks, to help reducing energy consumption and to allow a more cost-efficient management of the network; *iii)* the introduction of the novel "Radio Access Network-as-a-Service" (RANaaS) concept, as a flexible trade-off between full centralization (C-RAN) and decentralization ("traditional" implementation); *iv)* co-design of access and backhaul, enabling a joint optimization of the radio access network and a heterogeneous backhaul.

The rest of the paper is organized as follows. Section 2 describes in more details the key enablers and concepts. Section 3 focuses on the main challenges introduced by the joint design and optimization of radio access and backhaul networks. Finally, Section 4 concludes the paper, highlighting future challenges.

2. Key Enablers and Concepts for Future Mobile Networks

Increasing the spatial reuse of mobile networks is probably the most promising approach to achieve the previously described objectives. Since 1950, the system throughput of cellular networks rose by a factor of 1600 simply by increasing the density of the mobile network [4]. Small-cells exploit two fundamental effects; firstly, the distance between the radio access point (RAP) and user terminals is reduced and the data rate increases super-linearly by the inverse of the distance; secondly, the spectrum is re-used more often within the same geographic area which increases the overall efficiency. In 3GPP LTE, small cells draw more attention as a complement to existing macro-cellular deployments which provide coverage while small-cells increase the capacity in highly populated areas [5].

With an increasing network-density, the inter-cell interference increases as well and interference-scenarios become more complex. In addition, the average number of users per RAP may decrease which increases the chance that a RAP does not carry any traffic or only low traffic. For comparison, currently, about 15% of all sites carry about 50% of the total traffic [6]. This implies that a considerable amount of RAPs consume energy and computational resources unnecessarily.

With the centralization of computational resources, it is possible to implement efficiently inter-cell interference avoidance and mitigation algorithms at a central node. Furthermore, a centralized operation of mobile networks, as implemented by C-RAN [7] [8], allows for obtaining a globalized view on the allocated resources in order to optimize the resource usage (both, computational and energy resources). Hence, it is possible to shift efficiently resources between RAPs in order to maximize the resource usage.

In order to centralize the mobile network operation, high-capacity links between RAPs and the centralized point are required, which usually is only satisfied by optical fibre connections, e.g., in order to implement C-RAN for an LTE system with 20 MHz bandwidth, about 10 Gbps front-haul capacity is required. The usage of optical fibre makes C-RAN deployments less flexible and more cost-intensive, which implies a trade-off of benefits through centralized processing and the costs which are required to implement such a system.

Small-cells may be deployed where it is difficult or too expensive to deploy fixed broadband access for backhaul or line-of-sight (LOS) based microwave solutions. The Broadband Forum [9] reported that 30% of a mobile operator's OPEX today is spent for backhaul networks. Wireless backhaul gains more and more interest from operators due to its flexibility and cost-efficiency, even though wireless backhaul cannot provide the same achievable rates as optical fibre. Therefore, small-cell networks need to cope with a heterogeneous backhaul infrastructure consisting of wireless backhaul as well as high-capacity optical fibre.

In order to approach these key challenges, we consider the mobile network architecture depicted in Figure 1, which includes dense networks, heterogeneous backhaul, and flexible RANaaS. We consider small cell networks where RAPs are interconnected through heterogeneous backhaul, and RAN functionality is centralized flexibly by a RANaaS platform.

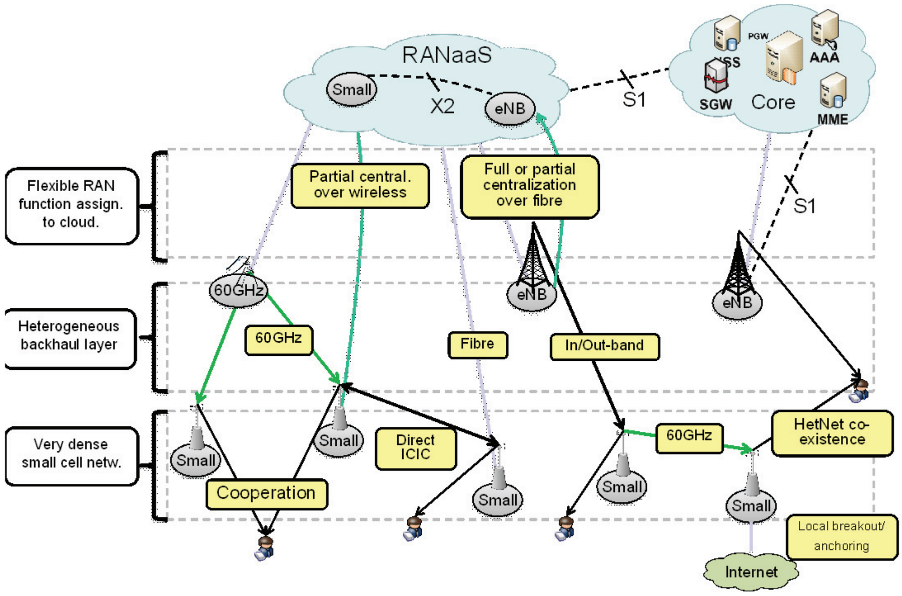

Figure 1 Considered mobile network architecture

3. Joint access/backhaul design: Challenges and Solutions

So far, radio access designs (including the 3GPP architecture) consider the backhaul network to be sufficiently dimensioned (over-provisioned). As backhaul requirements are becoming tougher, this assumption may not hold anymore, particularly, when we consider an increased centralization of the radio access network. In order to operate the mobile network optimally, it is necessary to consider both radio access and backhaul network jointly. The joint operation of both will allow for more flexibility of the mobile network operation. For instance, it is foreseen that the degree of centralization of the radio access network may be flexible, i.e. only parts of the evolved Node B (eNB) will be centralized. Only two extreme cases are considered now: either the eNB is fully centralized or it is fully decentralized. In the future, this degree of centralization may vary. One deciding parameter may be the available backhaul bandwidth, i.e. if more backhaul-resources are available, more functionality is centralized while if the network is backhaul-limited, less functionality is centralized.

However, currently deployed mobile networks, e.g., 3GPP LTE, do not provide the architectural means to allow for a joint operation of radio access and backhaul network. As outlined before, this co-design of radio access and backhaul network will be a key enabler to support the high diversity of quality of service (QoS) and data rates in future mobile networks. In the following, we will provide specific examples and resulting challenges for a co-design of radio access and backhaul network on physical layer, MAC/RRC layer, as well as for the network design.

3.1 Joint backhaul and radio access design

In conventional radio access technologies, the baseband signal processing takes place at the base station (or RAP in general). This local non-cooperative processing implies that each RAP only handles signals from/to user equipments (UEs) that are assigned to this RAP. Furthermore, the network must be dimensioned on the basis of the maximum expected load independent of the current needs.

In dense networks, several RAPs are usually in the range of one UE, so these co-located RAPs may process the received and transmitted signals jointly. This requires an adopted network architecture allowing for the efficient implementation with a multitude of spatially distributed nodes (RAPs) and a split of PHY functionality in the access network and centralised RAN processing. Thus, the boundaries between the access network itself and a heterogeneous backhaul – comprising different technologies such as fibre links, wireless links using the same frequency band as the RAN (in-band backhauling) and point-to-point radio links in different (possibly much larger frequency bands) – are blurred and a joint design of both becomes necessary. In order to develop such a new architecture, physical layer technologies are of interest which are capable to provide the required data rates and which can be flexibly operated based on backhaul layer parameters. Promising PHY techniques for partly/fully decentralized processing being adaptable to changing backhaul and access layer parameters are:

- Cooperative Multi-Point (CoMP) techniques that process jointly transmitted and received user signals. CoMP has been investigated by 3GPP [10] and under ideal conditions, where it provides significant gains for cell-edge users [11]. Recent initiatives (e.g., [12], [13], [14]) have revealed that those gains cannot be fully harnessed under practical constraints due to signalling and processing delays, signalling overhead, and limited backhaul capacities.
- Distributed estimation algorithms such as Distributed Turbo Processing [15], [16] require much more cooperation and information exchange between RAPs.
- In-Network-Processing (INP) [17], [18], [19], [20] is an iterative technique based on optimization and graph theory to achieve a consensus estimate at distributed nodes with

adjustable communication between these nodes. It permits cooperative symbol detection with reduced communication effort between the RAPs [21].

- Joint Network-Channel Coding aims to optimise jointly the wireless backhaul link and the access link by focusing on the code design at both source and RAPs [22].

For the joint access and backhaul design, the general question arises, at which point functionality can be split between the RAPs and the centralized unit (CU). For example, the signal processing chain at the receivers includes sampling, quantization, detection & decoding, ARQ as well as higher layer operations. Some of these processing steps can either be done in the RAPs or in the CU, resulting in different demands on link capacity and processing power. On the other hand, the wide range of backhaul technologies features different advantages and disadvantages in terms of range, availability, data rate and latency, all of which define constraints on the backhaul link. These backhaul capabilities may also vary with day time or weather conditions such that the functional split between the RAPs and the central unit has to be adjusted accordingly. In particular, the following approaches will help implementing links between the RAPs and the CU:

- Loss-less data compression techniques for fibre-backhaul using a “per user“-transmission method rather than traditional “per-cell“-methods in order to reduce the required data rates and provide more flexibility for backhaul-operation.
- Millimetre-wave (mmWave) backhaul links offer a large bandwidth, providing multi-Gigabit backhaul links even for small cells. This can be the basis for a wide range of techniques, from point-to-multipoint and multi-hop links to low-rate error correction codes for increased availability.
- Coding strategies are applied across the access and backhaul networks (e.g., joint backhaul-access-link design based on LDPC codes for in-band relaying).

In addition, the coordination of distributed transmission systems requires new approaches. In order to employ optimally the techniques, all involved effects and dependencies have to be evaluated and quantified, both from a theoretical point of view as well as by constant measurements in the actually deployed network. It is especially important, since the required exchange of information between different RAPs and the CU adds traffic to the already constrained backhaul network. A careful trade-off between different degrees of co-operation is needed, in order to ensure that improvements through information exchange are not nullified by the increased load on the backhaul network.

3.2 Joint access/backhaul RRM and novel backhaul solutions

The ever-increasing demand for higher data rate and ubiquitous wireless services had driven mobile operators to deploy local RAPs. As already mentioned, RAPs improve the network spectral reuse and result in hotspots where the distance between the end-user and the radio access is reduced. However, in such a scenario, a high number of RAPs with different characteristics may share the same spectrum in a given geographical area, which increases the inter-cell interference. In the past, interference management algorithms such as power control, interference cancellation, adaptive frequency reuse, and spatial cooperation, have been proposed mainly to improve performance of cell edge-users [23].

3GPP Release 9 introduced Inter-Cell Interference Coordination (ICIC) solutions where eNBs exchange information on the X2 interface [24] and limit the co-interference through dedicated schemes, which act in the power and frequency domains [25]. More recently, Release 10 has introduced enhanced ICIC (eICIC) mechanisms, which extend ICIC in the time domain and specifically target heterogeneous networks [26].

However, interference mitigation comes at the expense of system overhead and higher complexity, which are likely to be significant due to the large number of RAPs and the different types of backhaul links available for each type of cell. Hence, fully centralized solutions (like the C-RAN paradigm [27]) may not be a viable solution in this scenario

Heterogeneous networks, characterized by dense RAP deployment, require RRM solutions based on fundamental trade-offs amongst spectral efficiency gain, complexity, and signalling overhead. This optimization allows for exploiting central processing capabilities in eICIC algorithms across a large number of interfering small-cells while limiting overhead and complexity. In particular, it is necessary to derive flexible RRM algorithms for dense small cell deployments, where functionalities such as scheduling and interference mitigation are partly distributed at RAPs and partly executed at a CU.

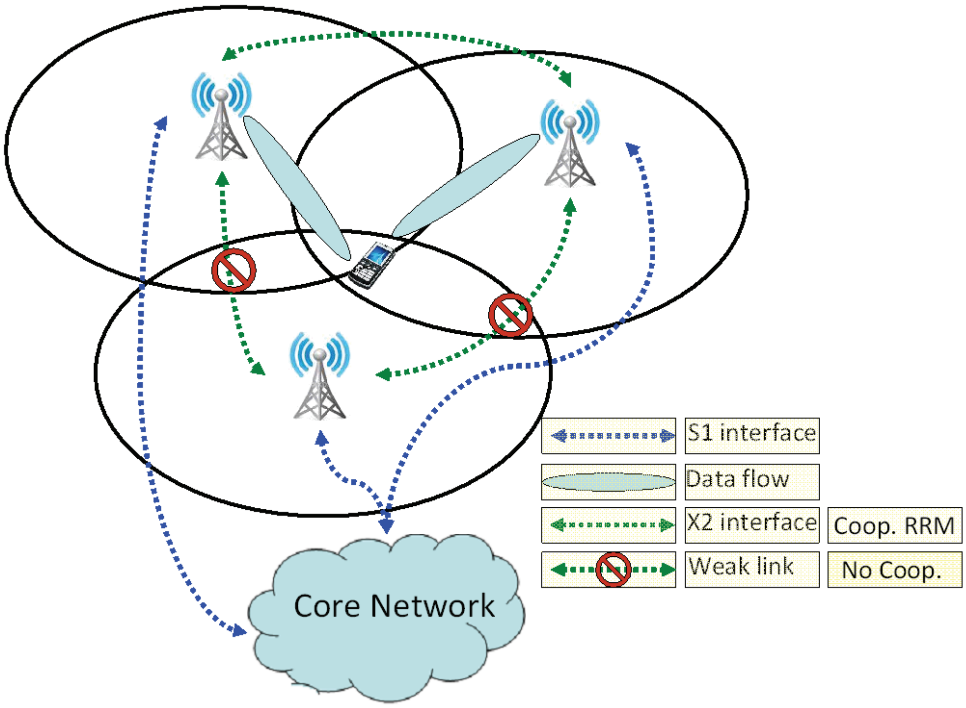

Figure 2 Flexible implementation of cooperative scheduling according to the backhaul capacity.

Furthermore, joint management of resources at the radio access and the heterogeneous backhaul is required to avoid bottlenecks while increasing the overall utilization efficiency. Diversity gains achieved by fast link adaptation or cooperative transmissions depend on the availability of updated channel state information, which on the other side increases overhead. To reduce this drawback, it is necessary to analyse more holistic and flexible MAC signalling that adapts to the current backhaul parameters, the centralisation requirements, and the actual access layer requirements. Moreover, reliable RRM mechanisms should be aware of the backhaul limits (such as latency and capacity) and adapt transmission parameters, accordingly (see Figure 2).

Finally, multi-hop wireless network with mmWave backhauling, which operates at 60 GHz technology, may provide up to 10 Gbps [28]. In this scenario, cell-clustering schemes are used to improve efficiency in the utilization of access and backhaul, both in terms of cost (energy spent in the overall network) and utilization (sustainable data rate, load balance). Specifically, one way forward is to cluster small cells and to let the network decide which small cells in a cluster can directly access the backhaul in order to efficiently optimize route selection and radio access resources.

3.3 *Network layer solutions for joint access/backhaul*

The network layer is of particular importance for small-cell deployments and centralised operation due to its ability to optimize data and user traffic patterns for both access and backhaul network. Supported by network-wide knowledge at a central entity, load can be distributed optimally within small-cell networks based on the granularity of information available in the CU. There are different challenges and solutions that we propose to tackle at the network layer, which we summarize next.

A first challenge is mobility within small-cell networks, which requires novel approaches due to more frequent handovers caused by smaller cells. Investigations focus on smart access network selection and efficient handover management in heterogeneous wireless environments taking into account backhaul restrictions as well as the current backhaul and access load situation. New schemes must minimize the service disruption time and switching cost while enabling effective load balancing.

Current mobile operator networks are suffering from different problems caused by high traffic offered loads. We propose to adopt a partly distributed mobility architecture, by contrast to current approaches, that rely on centralized control and data planes. We envision a fully distributed data plane, where generalized offload and local breakout of user data traffic is performed as soon as possible within the operator network and the control plane adopts different distribution characteristics depending on the network support.

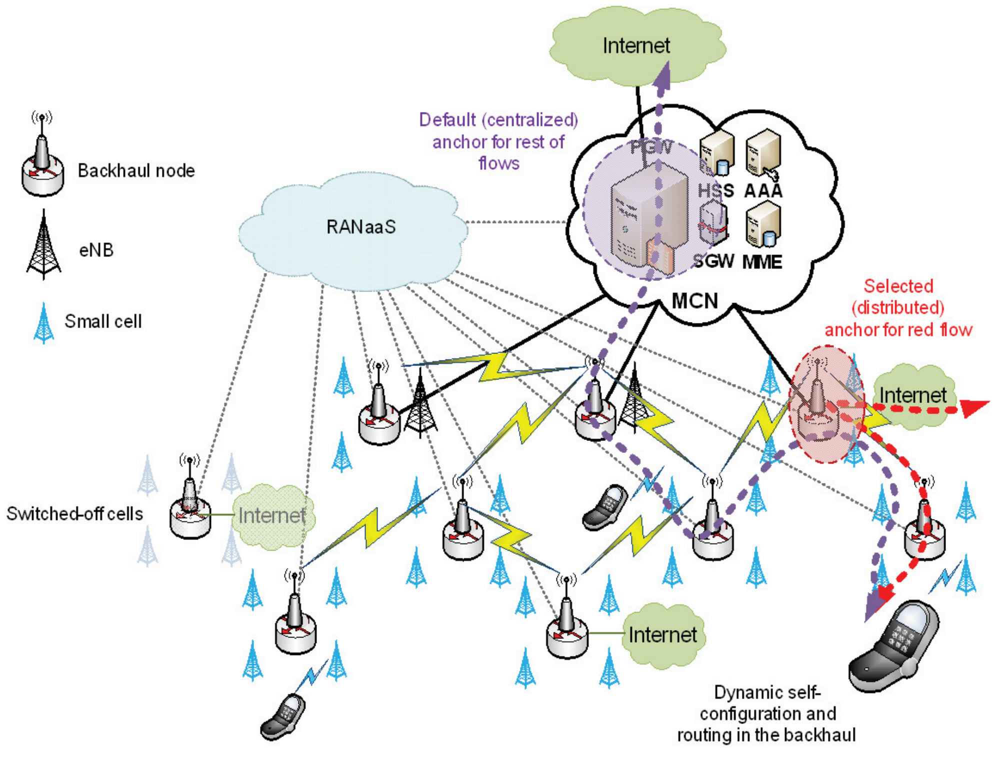

Figure 3 Distributed mobility management solution

Figure 3 shows an outline of the solution to be further developed to provide a dynamic IP distributed mobility support with offloading support. We summarize next the key points of the solution. The network has multiple nodes (in the access and in the backhaul) that can play the role of IP mobility anchors or offloading nodes. The difference between both is that the former can provide additional mobility support if the UE moves away from its area of influence, while the latter cannot. The UE and the network select the best radio access point and anchor for its traffic. If the UE moves and changes its cell (i.e. attaches to a different radio access point), some of the existing flows might need to be provided with mobility support. This is done by dynamically establishing/updating tunnels between the current radio access point and the original anchor of each IP flow. Note that this requires interaction with the backhaul routing function to ensure that each flow is provided with the necessary quality of service. In some cases, tunnelling can be avoided if the routing function is capable of performing the required traffic redirection. The required control signalling to enable this dynamic and smart IP anchoring functions will benefit from the logically centralized cloud infrastructure, to which all nodes have access to.

In order to optimize the cell load distribution, novel routing approaches for small-cell deployments and centralised processing are required. The most promising approach is to route cooperatively based on information about access and backhaul network, developing schemes to adapt flexibly parameters, e.g. the number of cooperation nodes and transmission power, dynamic network conditions and service requirements.

In order to guarantee user quality of service and experience, we are designing admission and congestion control algorithms with a holistic view of the network and with particular focus on the backhaul network. This will be achieved by taking into account backhaul and access resources, application traffic requirements and characteristics as well as the potential multiplexing gain on the backhaul link.

4. Conclusions

In this work we have presented the main challenges posed by a joint design of the backhaul and the radio access network in a cloud-based mobile network. The considered architecture aims at an efficient implementation of a multitude of spatially distributed nodes with a centralized RAN processing. In this architecture, the boundaries between the access network itself and a heterogeneous backhaul are blurred and a joint design of both that involves the three lower OSI layers becomes necessary.

The future work can be divided considering the three OSI layers involved. Regarding the physical layer, the focus is the development of techniques that are adaptable to frequently changing backhaul and access layer parameters. These are primarily partly-distributed algorithms that show a dependency on the constraints of the actual backhaul links. These algorithms comprise In-Network-Processing (INP) and Multi-Point Turbo Detection, as well as Coordinated Beamforming and Joint Network-Channel Coding.

As for the link layer, the work will be concentrated on partly distributed algorithms operating on smaller time-scales, taking into account backhaul constraints by investigating novel signalling schemes, novel backhaul technologies and energy efficient MAC protocols. These algorithms should address the challenge to RRM and backhauling, due to the inherently higher potential for inter-cell interference.

Regarding the network layer, the work will focus on mobility within the network, taking into account backhaul restrictions as well as the current backhaul and access load situation. Additionally, novel routing approaches that cooperatively route based on information about access and backhaul network will be proposed to optimize the cell load distribution. Finally, new admission and congestion control algorithms with a holistic view of the network and with particular focus on the backhaul network will be proposed.

References

[1] European Commission, "Digital Agenda Scoreboard 2011," Brussels, 2011.

[2] Nokia Siemens Networks, "2020: Beyond 4G, Radio Evolution for the Gigabit Experience," August 2011.

[3] European Commission, *Digital Agenda for Europe: key initiatives,* Brussels, May 2010.

[4] M. Dohler, R. Heath, A. Lozano, C. Papadias and R. Valenzuela, "Is The PHY Layer Dead?," *IEEE Communications Magazine,* no. 4, pp. 159-165, 2011.

[5] 3GPP, “TR 36.932, Scenarios and Requirements for Small Cell Enhancements for UTRAN and EUTRAN,” 3GPP, 2012.

[6] H. Guan, T. Kolding and P. Merz, “Discovery of Cloud-RAN,” in *Cloud-RAN Workshop*, April 2010.

[7] eMobility NetWorld, “Deliverable D1.1, White Paper on Broadband Wireless Beyond 2020,” June 2011.

[8] eMobility NetWorld, “Deliverable D1.2, Strategic Applications, Research and Innovation Agenda,” July 2011.

[9] “Broadband Forum - Home,” [Online]. Available: http://www.broadband-forum.org/. [Accessed 14 February 2013].

[10] 3GPP, “TR 36.819 Study on Coordinated Multi-Point Operation for LTE,” 2011.

[11] P. Marsch and G. P. Fettweis, Coordinated Multi-Point in Mobile Communications From Theory to Practice, Cambridge University Press, 2011, p. 508.

[12] EASY-C, “Enablers for Ambient Services and Systems Part C - Wide Area Coverage,” 2007. [Online]. Available: http://www.easy-c.com.

[13] ARTIST4G, “ARTIST4G project website,” 2009. [Online]. Available: www.ict-artist4g.eu.

[14] FUTON, “Fibre Optic Networks For Distributed, Extendible Heterogeneous Radio Architectures And Service Provisioning,” 2008. [Online]. Available: http://www.ict-futon.eu.

[15] T. Mayer, H. Jenkac and J. Hagenauer, “Turbo Base-Station Cooperation for Intercell Interference Cancellation,” in *ICC '06*, 2006.

[16] B. Zhao and M. Valenti, “Distributed turbo coded diversity for the relay channel,” *IEE Electronics Letters, vol. 39, no. 10,* pp. 786-787, May 2003.

[17] C. G. Lopes and A. H. Sayed, “Diffusion Least-Mean Squares Over Adaptive Networks: Formulation and Performance Analysis,” *IEEE Transactions on Signal Processing, Vol. 56, No. 7,* July 2008.

[18] I. Schizas, G. Mateos and G. B. Giannakis, “Distributed LMS for Consensus-Based In-Network Adaptive Processing,” *IEEE Transactions on Signal Processing, Vol. 57, No. 6,* June 2009.

[19] F. S. Cattivelli and A. H. Sayed, “Diffusion LMS Strategies for Distributed Estimation,” *IEEE Transactions on Signal Processing, Vol. 58, No. 3,* March 2010.

[20] H. Zhu, A. Cano and G. B. Giannakis, “Distributed Consensus-Based Demodulation: Algorithms and Error Analysis,” *IEEE Transactions on Wireless Communications, Vol. 9, No. 6,* June 2010.

[21] H. Paul, J. Fliege and A. Dekorsy, “In-Network-Processing: Distributed Consensus-Based Linear Estimation,” *IEEE Communications Letters,* vol. 1, pp. 59-62, January 2013.

[22] T. Tran, T. Nguyen and B. Bose, “A Joint Network-Channel Coding Technique for Single-Hop Wireless Networks,” in *Fourth Workshop on Network Coding, Theory, and Applications (NetCod 2008)*, Hong Kong, 2008.

[23] G. Bodreau, J. Panicker, N. Guo, R. Chang, N. Wang and S. Vrzic, "Interference Coordination and Cancellation for 4G Networks," *IEEE Communications Magazine,* pp. 74-81, April 2009.

[24] 3GPP, "TS 36.420: X2 general aspects and principles (Release 9)," March 2011.

[25] D .Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T.Q.S. Quek, and J. Zhang; , "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Communications* , vol.18, no.3, pp.22-30, June 2011

[26] 3GPP, "RP-111454: Status Report to TSG ; Enhanced ICIC for non-CA based deployments of heterogeneous networks for LTE – Performance part," in *TSG RAN meeting #54*, Berlin, Germany, December 2011.

[27] China Mobile Research Institute, "C-RAN - Road Towards Green Radio Access Networks," in *WWRF Meeting*, Dusseldorf (Germany), October 2011.

[28] N. Guo, R. C. Qiu, S. Mo and K. Takahashi, "60-GHz Millimeter-Wave Radio: Principle, Technology, and New Results," *EURASIP Journal on Wireless Communications and Networking,* 2007.

[29] European Commission, “Digital Agenda Scoreboard,” Brussels, May 2011.

[30] Cisco, “Cisco Visual Networking Index: Forecast and Methodology, 2010–2015,” June 2011.

[31] Cisco, “Cisco Vidual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015,” Cisco, February 2011.

[32] "148Apps.biz," [Online]. Available: http://148apps.biz/app-store-metrics/. [Accessed 14 February 2013].

[33] "Number of available Android applications - AppBrain," [Online]. Available: http://www.appbrain.com/stats/number-of-android-apps. [Accessed 14 February 2013].

[34] "Android Market Hits 10 Billion Downloads, Kicks off App Sale," [Online]. Available: http://www.wired.com/gadgetlab/2011/12/android-market-downloads/. [Accessed 14 February 2013].

[35] Net!Works European Technology Platform, "Broadband Wireless Beyond 2020," May 2011.