CROWD: An SDN Approach for DenseNets

Hassan Ali-Ahmad[1], Claudio Cicconetti[2*], Antonio de la Oliva[3], Martin Dräxler[4],
Rohit Gupta[5], Vincenzo Mancuso[3 6], Laurent Roullet[7], Vincenzo Sciancalepore[3 6]
[1]*Orange, France*, [2]*Intecs, Italy*, [3]*University Carlos III of Madrid, Spain*,
[4]*University of Paderborn, Germany*, [5]*Signalion, German*,
[6]*Institute IMDEA Networks, Spain*, [7]*Alcatel-Lucent Bell Labs, France*
[*] corresponding author e-mail: claudio.cicconetti@intecs.it
CROWD project: http://www.ict-crowd.eu/, @FP7CROWD

***Abstract*—Traffic demands in mobile networks are expected to grow substantially in the next years, both in terms of total traffic volume and of bit-rate required by individual users. It is generally agreed that the only possible solution to overcome the current limitations is to deploy very dense and heterogeneous wireless networks, which we call *DenseNets*. However, simply scaling down existing networks by orders of magnitude, as required to fulfill traffic forecasts, is not possible because of the following constraints: i) the bottleneck would shift from the Radio Access Network (RAN) to the backhaul; ii) control overhead, especially related to mobility management, would make the network collapse; iii) operational costs of the network would be unbearable due to energy consumption and maintenance/optimisation. In this paper, Software Defined Network (SDN) for mobile networks is claimed as the paradigm shift necessary to tackle adequately the above challenges. A novel architecture is proposed, which supports DenseNets made of overlapping LTE and WLAN cells connected to the core network via a reconfigurable backhaul.**

I. Introduction

In the world of mobile radio networks we are witnessing a singularity for what concerns their deployment and usage. In fact, while pervasive computing and similar paradigms have been long theorised, e.g., [1], only recently the economic-technological advances, including the diffusion of mobile Broadband Wireless Access (BWA) networks, the rise of social networks, and the very high penetration of smart phones/tablets, have turned the dream into a reality. As a matter of fact, mobile users now demand high bit-rate, and there are already applications in the waiting list to exploit such potential, along with business makers looking forward to creating new revenue streams. Examples include mobile video [2], which goes both directions, unlike traditional broadcasting or YouTube, and cloud computing applications, whose growth has been predicted as sky-rocketing since a few years and will likely reach its climax soon [3]. All these factors combined have convinced the telecommunications industry that an exponential increase of mobile data is expected, in the order of $1000\times$ increase by 2020 [4].

Quite clearly, the growth foreseen cannot be sustained only by increasing the spectrum assigned to mobile radio networks. In fact, spectrum availability is already scarce in the ranges of practical interest, and spectral efficiency achieved by today's technologies like Long Term Evolution (LTE) is already very close to Shannon's limit. This leaves only one possible option: to densificate wireless networks [5]. However, such densification cannot be done as a mere rescaling of existing protocols/networks because of the following primary reasons:

1) Backhaul networks cannot be easily scaled down, since the installation of new cabled infrastructure requires more substantial investments than the deployment of wireless access points, especially indoor [6].
2) Existing network protocols have been designed to operate efficiently only for the current density levels, but they easily become a performance bottleneck when pushed further, e.g., too frequent mobility management messages are exchanged unnecessarily [7].
3) Massive deployment of new base stations and interconnecting network elements creates an additional burden to operators, and the society at large, in terms of energy consumption [8].

To cope with all the issues mentioned above we need a novel and dynamic solution which provides: *specialised and fine-grain optimisation mechanism* and *dynamic and "high density proof" provisioning of resources*. The emerging Software Defined Network (SDN) paradigm [9] is therefore a natural candidate to design an architecture able to provide and manage the required network solutions.

In this paper we describe the initial results obtained in Connectivity management for eneRgy Optimised Wireless Dense networks (CROWD), a collaborative project funded by the European Commission under the Seventh Framework Programme. The goal of CROWD is to design protocols and algorithms for very dense and heterogeneous wireless networks, which we call *DenseNets*.

The remainder of this paper is structured as follows. In Section II we elaborate on the motivation for an SDN approach to DenseNets and existing related approaches. Our proposed network architecture is illustrated in Section III, whereas the concrete challenges towards the realisation of SDN in LTE and Wireless Local Area Network (WLAN) networks are described in Section IV. Conclusions are drawn in Section V.

II. SDN motivation

The need to introduce re-configurability in the wireless world has been widely identified as a key requirement to efficiently deploy and maintain converged networks. This has been acknowledged to some extent by recent standards

978-1-4799-2433-2/13 $31.00 © 2013 IEEE
DOI 10.1109/EWSDN.2013.11

(including techniques that range from adaptive beam-forming or flexible OFDMA subcarrier structures to configurable MAC parameters), as well as by other ongoing standardisation efforts for defining Reconfigurable Radio Systems (RRS) [10]. Moreover, manufacturers are working on the development of an inter-operable Software Communication Architecture [11] for Software Defined Radio (SDR). However, the approaches above focus on the optimisation via dynamic reconfiguration of a single device (terminal or base station).

Furthermore, network-wide automatic self-configuration has been heavily investigated within the LTE standard for Evolved NodeBs (eNBs) (e.g., [12]), and for WiFi Access Points (APs), focusing, among others, on IP address configuration [13], channel assignment and AP selection [14]. This is the Self Optimising Network (SON) approach, which has been envisioned for the optimisation of networks using a single radio technology.

Although some initial proposals on SON for heterogeneous networks appeared in the literature (e.g., [15]), practical realizations under realistic assumptions (e.g., under imperfect channel state estimation, constrained communication between base stations, and small cells which make the distributed solutions complex and less reliable) are largely lacking.

Existing solutions like SDR or SON do not provide suitable control and optimisation mechanisms for DenseNets. In fact, in DenseNets, SDR or SON making localised control decisions could result in wireless chaos. For example, configuring Medium Access Control (MAC) parameters for WLANs only based on the scope of a single AP could result in a high level of harmful interference with a high number of surrounding APs. Similarly, in LTE, extending the current neighbourhood coordination via the X2 interface to the high number of base stations present in DenseNets would result in unmanageable amount of overhead. Therefore, we see a clear need for a paradigm switch on how to control network elements.

Indeed, due to density and heterogeneity of DenseNets, we need a clear split between *where* the *control decisions* are made and where the resulting *control actions* are enforced. On one hand, the control decisions have to be made on a scope that is broad enough to avoid a myopic focus on a very localised part of the network. On the other hand, the control actions have to be executed in a fast and precise manner to be effective. Thus control actions cannot be executed on the same broad scope as the one in which decisions are made.

The split between control decisions and control actions will also decouple network Technology-Specific (TS) functions and Technology-Agnostic (TA) functions: The enforcement of control actions still has to be implemented on TS network functions and Application Programming Interfaces (APIs), whereas control decisions could be made based on either a TS or TA level of abstraction. According to our point of view, this approach is in line with the definition of SDN, recently emerging as a successful alternative to traditional network management [9], especially for high-speed transport network elements. In fact, SDN enables controlling traffic flows by means of a central controller and simple, yet powerful, APIs. In particular, the outlined split between control decisions and control actions in DenseNets is very similar to the OpenFlow [16] architecture, which is the most well-known SDN instance, with a controller being in charge of making routing decisions and the switches executing these decisions. Therefore, in CROWD, we propose to adopt an SDN paradigm.

Some effort has been recently made in the specific context of SDN for wireless systems. For instance, Odin [17] deals with enterprise WLANs and proposes to extend an existing OpenFlow controller to handle AP clients as if they were connected to different ports of a switch. CloudMAC [18] introduces some other OpenFlow extensions for coordinating the access operations between different APs, whereas Dyson [19] proposes a simple interface for configuring the radio links. Following a more holistic approach, the authors in [20] propose an advanced abstraction model, that allows to program the baseband (composing different modulation actions) and the rules for classifying the traffic packets and triggering the relevant actions. These rules extend OpenFlow by considering additional PHY-related fields for the incoming packets, such as the received signal strength and the modulation format. Furthermore, OpenRoads [21] provides support for mobility management solutions by using OpenFlow. However, these existing wireless SDN solutions do not consider how to scale up to a network-wide perspective in dense and heterogeneous wireless access networks. For instance, we argue that having one static, centralised controller is not a feasible solution taking into account the density of the network and the expected computational overhead. Moreover, controllers have to be able to manage a broad range of dynamics happening at very different time scales, due to the heterogeneity of DenseNets. In contrast, our envisioned control functions range from very fast, short-time-scale functions, executed close to the involved network equipment, to longterm functions involving larger parts of the backhaul network.

Therefore, in CROWD we propose a dynamic, two-tier SDN controller hierarchy with two types of controllers:

1) The CROWD Local Controller (CLC) which can take fast, short time scale decisions on a limited but fine grain scope.
2) The CROWD Regional Controller (CRC) which can take slower, long time scale decisions with a broader but more coarse grain scope.

This two-tier approach allows us to better aggregate control information (i.e., reduce signalling overhead) when details are not required on a broader scope. These two types of controllers are the central parts of our overall architecture which we describe in the next section.

III. Architecture

In this section we provide a high-level overview of the proposed network architecture. It encompasses LTE (macro/pico/femto) and WiFi cells, which are the technologies expected to have the highest penetration in mass deployments in the future. We assume in the following that all the network elements belong to the same administrative domain and we neglect the security measures which must be implemented in practice to prevent malicious access of the control functions and to avoid unauthorised disclosure of sensitive information from customers.

As discussed above our architecture is structured into two logical tiers: *districts* with a limited, but fine grain scope for short time scales, and *regions* with a broader but more coarse grain scope for long time scales.

A *district* consists of base stations, i.e., LTE eNBs and WiFi APs, as well as interconnecting backhaul links that are assumed without loss of generality to be reconfigurable via some open protocol, e.g., OpenFlow (OF). Operation within a district is optimised by applications connected to the CLC via a set of APIs, called North Bound (NB) interface in the SDN terminology. We forsee least two types of NB APIs:

1) *Technology-Specific (TS)*, which expose fine-grained details as acquired from the base stations (e.g., sub-frame utilisation in LTE) and offer methods which are only valid for the specific communication protocol (e.g., change Congestion Window (CW) in a WiFi AP)
2) *Technology-Agnostic (TA)*, which expose abstract and aggregated data (e.g., average node utilisation) and offer generic modifiers which may be valid for a wide range of technologies and capabilities (e.g., switch off a node).

Any application can connect to one or more APIs, depending on its optimisation goals and requirements. Based on the technologies present in the disrict, the CLC can access different South Bound (SB) interfaces for LTE and WiFi to control the wireless operations and OF for controlling the backhaul network. An overview on the CLC interfaces is shown in Fig. 1.

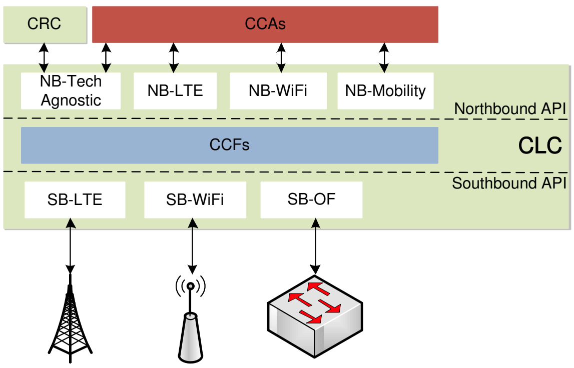

Fig. 1: CLC architecture and interfaces

A special use of the technology-agnostic API is to connect a CLC to its higher-level controller, the CRC, which operates inside a *region*. The region is defined as a logical area including several districts in which technology-agnostic applications are executed for longer scale optimisations, compared to the CLC applications. Regional optimisation is proposed to compensate sub-optimal choices which may be taken at district level because of the myopic sight of the local controllers.

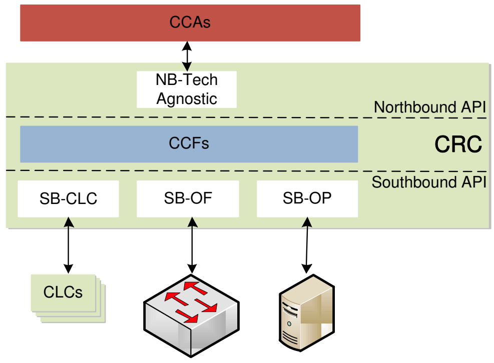

Fig. 2: CRC architecture and interfaces

Thus the CRC only exposes a TA interface on its NB API for regional CROWD Control Applications (CCAs). The SB of the CRC include a specific interface to control CLCs inside the region and interfaces to the OF backhaul network and for information exchange with the network operator (OP) infrastructure.

A simplified example for the interaction between the CLC and the CRC is the follwoing: From the point of view of an application running within the CLC with the goal of minimising energy consumption, an “optimal” choice could be forcing all user terminals to associate to APs outside of the district and switching off all the network elements. Such a drastic decision would be obviously sub-optimal from a broader network viewpoint, thus any CRC application aiming to minimise energy consumption would certainly override it.

A diagram of the architecture is reported in Fig. 3, which also shows the SB interfaces between the CLC and the base stations and backhaul, as well as some key interconnections with new and existing network elements.

For instance, in the case of LTE, the eNBs have a split connection: the control path, i.e., via the Third Generation Partnership Project (3GPP) S1-MME and X2 interfaces, goes entirely through the CLC, whereas the data path is directed to the Distributed Mobility Management (DMM) Gateway (GW), which is a novel element proposed in CROWD, as described in Section IV. Therefore, a CLC application can interject the communication between the eNB and the Mobility Management Entity (MME) and anticipate/override intra-district mobility decisions. Note also that we propose the use of the X2 interface for collecting fast and detailed measurements from the LTE eNBs, since it already supports a wide range of data, even though the standard assumes that information is exchanged between peer eNBs.

IV. Controller Functions and Applications

In this section, we first present an overview of our planned short-term optimization mechanisms, aimed at enhanced wireless MAC operations. Then, we present the long-term mechanisms, focused on dynamic radio and backhaul configuration, as well as on connectivity management.

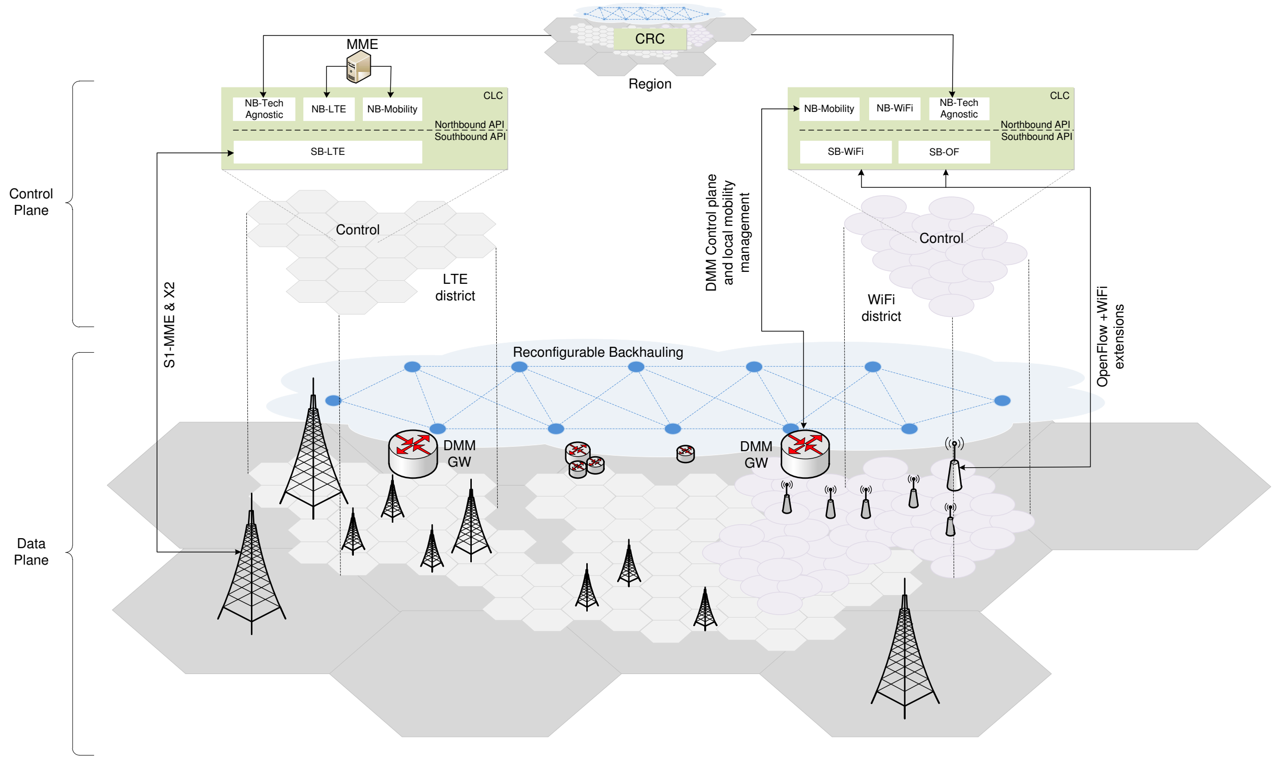

Fig. 3: CROWD network architecture.

A. Enhanced Wireless Mechanisms

Controlling the operation of a DenseNet includes the coordination and control of radio and MAC operations for both LTE and WLAN devices. We focus on radio/MAC adaption mechanisms required on the short-term operation time-scale to efficiently use network resources when hundreds or thousands of devices need to be automatically and timely controlled by CLCs. Thereby, the SDN approach represents an efficient and powerful solution to implement the CLC defined in the CROWD architecture to take care of radio and MAC operation control.

Using SDN, the control plane is directly implemented in a software application which runs the stateful algorithmic operations, hereafter called CCA, and represents the logical decision core. CCAs use the NB APIs of the CLC to fetch input data and issue reconfiguration commands. Then, the commands are processed by a set of CROWD Control Functions (CCFs), which are internally deployed in the CLC. CCFs offer a stateless set of mechanisms to connect NB and SB APIs in the controller, thus providing the required services to the application layer running above NB APIs. In what follows, we present some relevant examples of challenging CCAs, which are relevant for standard and innovative operations in DenseNets.

Let us first consider LTE Applications. We define *Enhanced Inter-Cell Interference Coordination (eICIC)* as the application which aims to orchestrate LTE transmission activities within a local area covered by multiple LTE eNBs and HeNBs. This application requires monitoring and filtering of interference statistics, by using specifically the Monitoring/Filtering CCF, and then decides how to coordinate transmissions, e.g., by temporarily inhibiting transmissions at a particular eNB and/or HeNB by issuing Almost Blank Sub-Frame (ABSF) commands through the *ABSF Control* CCF (see Table I). Furthermore, we also identify the *Device to Device (D2D) offloading* as a potential LTE CCA. In particular, this application is in charge of deciding when and how LTE transmissions should be offloaded to users adopting the D2D paradigm. Moreover, the D2D offloading application could decide whether users can form clusters whose cluster leader relays the LTE traffic for all cluster members using WLAN connectivity (e.g., WiFi Direct). As a result, D2D offloading would require the availability of stateless CCF such as Network Discovery, Topology Detection, Scheduling Policy Control, Relay Management, etc., to run on the CLC (see Table I).

Regarding WLAN CCA, we mention *WLAN Optimisation*, which is meant to run optimisation algorithms to tune transmission and power parameters of WLAN devices. This application accounts for standard 802.11 tuning by using the WiFi parameter setting CCF, as listed in Table I, while offering an automatic tool for device reconfiguration, based on live network stats. Moreover, non-standard operations can be accounted for by introducing new advanced CCAs. For instance, we propose *AP Cooperation* as a specific application for coordinating multiple 802.11 APs to cooperatively decode uplink transmissions, with no need to send acknowledgments

TABLE I: CROWD Control Functions for CLC

CROWD Control Function	**CROWD Control Applications using the function**	NB_{LTE}	NB_{WiFi}	NB_{TA}	SB_{LTE}	SB_{WiFi}	SB_{OF}
Monitoring/Filtering	eICIC, Access Selection, Load Balancing, WLAN Optimization	•	•	•	•	•	
Network Discovery	eICIC, Access Selection, Load Balancing, D2D Offloading	•	•	•	•	•	
Power Control Setting	eICIC	•			•		
Access Selection Setting	Access Selection, Load Balancing, D2D Offloading	•	•	•	•	•	
Scheduling Policy Control	eICIC, D2D Offloading	•			•		
ABSF Control	eICIC	•			•		
Content Management	D2D Offloading	•			•		
Relay Management	Access Selection, D2D Offloading	•	•		•	•	•
AP Packet Retention Control	AP Cooperation		•			•	•
WiFi parameter setting	WLAN Optimization		•			•	
Subframe Synching	eICIC, D2D Offloading	•	•		•	•	

to the transmitting 802.11 stations. However, the ack-less operational mode is convenient only when all transmissions can be decoded with high probability, so that a controller is needed to decide when it can be enabled.

Finally, some CCAs are TA. For instance, *Access Selection* is meant to feed mobile users with information about available access networks (either LTE or WLAN). Access Selection needs to collect info on network topology and utilisation (e.g., not only on the availability and load of points of access, but also on D2D relay nodes) by means of CCFs, and then instruct all network's points of access on access selection settings to present to mobile devices. Therefore, Access Selection operation is relevant for optimising network entry and hand-over procedures, including vertical hand-over. Another example of TA CCA is *Load Balancing*, which is particularly challenging in DenseNets since wireless paths can suffer high interference and the achievable throughput over a path is correlated to the utilisation of interfering paths. Therefore load balancing requires the coordination of both LTE and WLAN resources.

As reported in Table I, some CCFs need to interface to specific LTE or WLAN devices, and therefore they use the LTE SB API or the WiFi SB interface. Some other CCFs act on the data forwarding plane, e.g., by modifying forwarding tables, thus requiring the use a modified OpenFlow API.

B. Dynamic radio and backhaul configuration

The previously presented mechanisms focus on short-term optimisation of radio parameters on a fine-grain, local scope executed at the CLC. Here we focus on long-term optimisation mechanisms on a regional scope executed at the CRC. These mechanisms do not need all decision input from the local scope and will work on a level of abstraction to avoid unnecessary control overhead.

In DenseNets we cannot provision network resources solely based on static planning, especially in the case of backhaul resources. Even with today's network densities and radio access technologies, the backhaul network is often already highly utilised. Existing work [22], [23] shows that dynamic backhaul network reconfiguration can help to utilise backhaul network resources better and to enable serving a higher number of users in the network. We want to extend this approach for future DenseNets. Because of the high level of flexibility in the backhaul network required to implement these mechanisms, we argue that our proposal can be efficiently implemented with the SDN approach. Table II gives an overview of the related CCFs and CCAs and the used SB interfaces of the CRC. Here we focus on two mechanisms we develop in CROWD: *controller life cycle management* and *traffic-proportional backhaul reconfiguration*.

The control functions for short-term decisions, like MAC adaptation, have to be run in an execution environment that provides the necessary decision input and fast access to the network equipment to enforce these decisions. Setting up this execution environment is part of the core functionalities of the CRC. It allows a control application to specify its input and output requirements and will determine the best placement in the network where CCAs should be executed. The particular challenge in this task is in the location decision. Depending on the concrete requirements, this easily turns into an NP-complete problem, closely related to clustering problems and the facility location problem with inverse costs functions. We call this placement of controllers and setting up the execution environment *controller life cycle management*. This problem has also been investigated for SDN deployments in general [24], but without focussing on the specific challenges from DenseNets and a two-tier controller hierarchy.

Directly linked to the controller life cycle management is the *traffic-proportional backhaul reconfiguration*. If controllers cannot be placed in a satisfying way regarding the available capacity of the backhaul network, we can dynamically provision additional backhaul resources. Reconfiguring parts of the backhaul network results in a larger search space for controller location and allows more efficient placements. On the other hand, the same reconfiguration mechanisms can be used to

TABLE II: CROWD Control Functions for CRC

CROWD Control Function	**CROWD Control Applications using the function**	NB_{TA}	SB_{OF}	SB_{CLC}	SB_{OP}
Topology and network element discovery and monitoring	Powercycling, Long-term clustering	•	•	•	•
Controller placement and lifecycle management	Long-term adaption of radio parameters, Long-term clustering	•		•	
Backhaul management	Powercycling, Traffic-proportional backhaul reconfiguration	•	•		

decrease backhaul resources where they are not needed. This allows to operate the backhaul network in a more traffic-proportional way. Combining this application with the power cycling of eNBs and APs we can increase the energy efficiency across the whole network.

Both of these mechanisms rely on the ability of the backhaul network to be reconfigured. We argue that OpenFlow-based backhaul networks provide the necessary features for the backhaul network reconfiguration. OpenFlow is also being extended for a tighter integration with current physical backhaul technologies like optical WDM-PON networks [25], [26]. In WDM-PON backhaul networks it is possible to flexibly configure and reconfigure the used of backhaul resources based on the dynamic routing of optical wavelengths.

C. Connectivity Management

Connectivity management is a key issue in current operators networks. Enabling service continuity for users while on the move has proved to be a major challenge that is, in fact, shaping the architecture of current and future networks. While providing mobility to the user is seen now as a key service that users take as granted, in the future DenseNets, mobility management will be a critical operational factor for the network operators. In particular, smart management of the user association and traffic routing are the key to the success of communications in dense scenarios. Through anintelligent association management, the network shall assist the terminal in choosing the best point of attachment considering not only terminal's requirements but also network optimisation factors such as backhaul capacity, access point/base station load, energy consumption, etc.

As for routing, in order to overcome scalability problems and bottlenecks typical of existing centralized architectures, the IETF is already working in distributed versions of its mobility protocols, which can be used to provide a flatter network architecture, allowing user's traffic to be offloaded to the Internet as near as possible to the user, hence reducing the load in the operator core. One of the main characteristics of these solutions is that the terminal will always start new connections with a prefix valid on its current point of attachment, while connections started in previous points of attachment will be forwarded to the current one. This implies that the cost of using this solution increases with the number of handovers and the duration of the flows. Due to these scalability properties, the use of such distributed approaches in DenseNets falls short, since the number of handovers in a extremely dense scenario will be at least an order of scale higher than in current networks.

The mechanisms we are currently designing in CROWD for the management of mobility benefit of SDN concepts to overcome the above mentioned challenges. The main building blocks of our architecture are: control and data plane split, and access selection. First, connectivity management can highly benefit from the *separation between control and data paths* provided by SDN approaches. Basically through this separation we are able to control the path of the actual data flows addressed to the terminal. We do this in a two-stage approach. First, we provide an OpenFlow-like management of the mobility at district level (e.g., providing mobility management without IP change within an IEEE 802.11 network up to the gateway to Internet). Second, we provide IP mobility support through the use of DMM solutions. As far as *access selection*, current SDN approaches focus on the control of the data path through the different networks. Hence, SDN is regarded as a technology of the core.

One of the first attempts to implement SDN concepts for managing the terminal can be found in IEEE 802.21 specifications. IEEE 802.21 defines an abstraction layer that uses abstract but medium-dependent primitives (LINK_SAP) to control lower layers of the terminal (SB) while providing a common set of primitives for the applications to control user's mobility in a media-independent way (MIH_LINK_SAP, NB). In CROWD, we consider the use of this technology to control access selection operations, providing smart mechanisms to optimise the network through the management of users's mobility. The main challenges of our approach are as follows.

First, *a common southbound interface for managing data path*. The scenario being tackled in CROWD is built on LTE and IEEE 802.11 technologies. One of the requirements for controlling the mobility of the user is being able to affect and decide the path followed by its traffic. For the case of IEEE 802.11 access points connected through IEEE 802 technologies (i.e., any IEEE 802.1 standard) OpenFlow could be used, but it cannot be used for the LTE part, since the underlying technology in completely different and not compatible with the IEEE 802.1 bridging used by OpenFlow. Hence, it is required to define a new SB interface suitable for the LTE technology.

Second, *the application of SDN concepts to different layers of the protocol stack*. SDN allows to programmatically tackle the control of the network. This means, for istance, that an application may handle the data path used by user's flows.

Current approaches are built on top of basic connectivity layers, such as layer 2 forwarding in the case of OpenFlow. In order to truly be able to write applications that handle mobility of the users in a holistic way, considering inter-domain and inter-technology scenarios, it is needed to define SDN hooks or APIs for the different layers of the protocol stack, providing functionality that cannot be provided by lower layers. As an example, it is necessary to provide APIs for the authorisation of users, which at lower layers will require complex setups.

V. Conclusion

In this paper we have described the network architecture proposed in CROWD for the efficient operation of DenseNets, i.e., heterogeneous and very dense wireless networks. Our approach fully endorses the SDN principles of control vs. data path separation and dynamic reconfigurability of the network elements. We have then identified the major challenges ahead for three important aspects: MAC layer reconfiguration, dynamic backhaul reconfiguration, and connectivity management. Future activities within the project will lead to the detailed definition of open interfaces for local and regional controllers, and to the design of prototype controllers and optimisation applications.

Acknowledgment

The research leading to these results has received funding from the European Unions Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 318115 (Connectivity management for eneRgy Optimised Wireless Dense networks – CROWD). Further details about the project can be found in the website http://www.ict-crowd.eu/. To receive news you can follow the twitter channel @FP7CROWD.

References

[1] D. Saha and A. Mukherjee, "Pervasive computing: a paradigm for the 21st century," *IEEE Computer*, vol. 36, no. 3, pp. 25–31, 2003.

[2] K. Ma, R. Bartos, S. Bhatia, and R. Nair, "Mobile video delivery with HTTP," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 166–175, 2011.

[3] J. Zander and P. Mahonen, "Riding the data tsunami in the cloud: myths and challenges in future wireless access," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 145–151, 2013.

[4] [Online]. Available: http://www.qualcomm.com/1000x

[5] K. Mallinson, "202 Vision for LTE," Report, June 2012.

[6] W. Wang, G. Yu, and A. Huang, "Cognitive radio enhanced interference coordination for femtocell networks," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. –, 2013.

[7] K. Pedersen, P. Michaelsen, C. Rosa, and S. Barbera, "Mobility enhancements for LTE-advanced multilayer networks with inter-site carrier aggregation," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. –, 2013.

[8] X. Xu, G. He, S. Zhang, Y. Chen, and S. Xu, "On functionality separation for green mobile networks: concept study over LTE," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. –, 2013.

[9] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 114–119, 2013.

[10] M. Mueck, A. Piipponen, K. Kalliojarvi, G. Dimitrakopoulos, K. Tsagkaris, P. Demestichas, F. Casadevall, J. Pérez-Romero, O. Sallent, G. Baldini, S. Filin, H. Harada, M. Debbah, T. Haustein, J. Gebert, B. Deschamps, P. Bender, M. Street, S. Kandeepan, J. Lota, and A. Hayar, "ETSI reconfigurable radio systems: status and future directions on software defined radio and cognitive radio standards," *IEEE Commun. Mag.*, vol. 48, no. 9, pp. 78–86, 2010.

[11] C. Gonzalez, C. Dietrich, and J. Reed, "Understanding the software communications architecture," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 50–57, 2009.

[12] H. Hu, J. Zhang, X. Zheng, Y. Yang, and P. Wu, "Self-configuration and self-optimization for LTE networks," *IEEE Commun. Mag.*, vol. 48, no. 2, pp. 94–100, 2010.

[13] E. Ancillotti, R. Bruno, M. Conti, and A. Pinizzotto, "Dynamic address autoconfiguration in hybrid ad hoc networks," *Pervasive and Mobile Computing*, vol. 5, no. 4, pp. 300–317, 2009.

[14] B. Kauffmann, F. Baccelli, A. Chaintreau, V. Mhatre, K. Papagiannaki, and C. Diot, "Measurement-Based Self Organization of Interfering 802.11 Wireless Access Networks," in *26th IEEE Int. Conf. on Computer Communications (INFOCOM)*, 2007.

[15] M. Peng, D. Liang, Y. Wei, J. Li, and H.-H. Chen, "Self-configuration and self-optimization in LTE-advanced heterogeneous networks," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. –, 2013.

[16] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "OpenFlow: enabling innovation in campus networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, Mar. 2008.

[17] L. Suresh, J. Schulz-Zander, R. Merz, A. Feldmann, and T. Vazao, "Towards programmable enterprise WLANS with Odin," in *Proc. of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012.

[18] J. Vestin, P. Dely, A. Kassler, N. Bayer, H. Einsiedler, and C. Peylo, "CloudMAC: towards software defined WLANs," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 16, no. 4, pp. 42–45, Feb. 2013.

[19] R. Murty, J. Padhye, A. Wolman, and M. Welsh, "Dyson: an architecture for extensible wireless LANs," in *Proc. of the 2010 USENIX conf.*, ser. USENIXATC'10. Berkeley, CA, USA: USENIX Association, 2010.

[20] M. Bansal, J. Mehlman, S. Katti, and P. Levis, "OpenRadio: a programmable wireless dataplane," in *Proc. of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. New York, NY, USA: ACM, 2012.

[21] K.-K. Yap, M. Kobayashi, R. Sherwood, T.-Y. Huang, M. Chan, N. Handigol, and N. McKeown, "OpenRoads: empowering research in mobile networks," *SIGCOMM Comput. Commun. Rev.*, vol. 40, no. 1, pp. 125–126, Jan. 2010.

[22] M. Dräxler, T. Biermann, H. Karl, and W. Kellerer, "Cooperating base station set selection and network reconfiguration in limited backhaul networks," in *IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, 2012.

[23] M. Dräxler, T. Biermann, and H. Karl, "Improving Cooperative Transmission Feasibility by Network Reconfiguration in Limited Backhaul Networks," *International Journal of Wireless Information Networks*, vol. 20, no. 3, pp. 183–194.

[24] B. Heller, R. Sherwood, and N. McKeown, "The controller placement problem," in *Proceedings of the first workshop on Hot topics in software defined networks*, ser. HotSDN '12. ACM, 2012, pp. 7–12.

[25] D. Simeonidou, R. Nejabati, and S. Azodolmolky, "Enabling the future optical Internet with OpenFlow: A paradigm shift in providing intelligent optical network services," in *Transparent Optical Networks (ICTON), 2011 13th International Conference on*, 2011.

[26] S. Azodolmolky, R. Nejabati, S. Peng, A. Hammad, M. P. Channegowda, N. Efstathiou, A. Autenrieth, P. Kaczmarek, and D. Simeonidou, "Optical FlowVisor: An OpenFlow-based Optical Network Virtualization Approach," *National Fiber Optic Engineers Conference*, p. JTh2A.41, 2012.