An SDN-based Network Architecture for Extremely Dense Wireless Networks

Hassan Ali-Ahmad[1], Claudio Cicconetti[2*], Antonio de la Oliva[3],
Vincenzo Mancuso[4], Malla Reddy Sama[1], Pierrick Seite[1], Sivasothy Shanmugalingam[1],
[1]*Orange, France*, [2]*Intecs, Italy*, [3]*Universidad Carlos III de Madrid, Spain* [4]*IMDEA Networks, Spain*
[*] corresponding author e-mail: claudio.cicconetti@intecs.it
CROWD project: http://www.ict-crowd.eu/, @FP7CROWD

***Abstract*—Telecommunications networks are undergoing major changes so as to meet the requirements of the next generation of users and services, which create a need for a general revised architectural approach rather than a series of local and incremental technology updates. This is especially manifest in mobile broadband wireless access, where a major traffic increase is expected, mostly because of video transmission and cloud-based applications. The installation of a high number of very small cells is foreseen as the only practical way to achieve the demands. However, this would create a struggle on the mobile network operators because of the limited backhaul capacity, the increased energy consumption, and the explosion of signalling. In the FP7 project CROWD, Software Defined Networking (SDN) has been identified as a solution to tame extreme density of wireless networks. Following this paradigm, a novel network architecture accounting for MAC control and Mobility Management has been proposed, being the subject of this paper.**

I. Introduction

Recently, mobile users demand on data traffic is increasing dramatically. Operators statistics show that the usage of mobile data traffic has doubled during the last year [1]. This is expected to continue in this decade especially with the deployment of 4G networks, resulting in an explosion in mobile Internet traffic. In order to cope with such rapid explosion, mobile network operators have already started to push for denser, heterogeneous deployments [2]. Indeed, current technology needs to steer towards efficiency, to avoid unsustainable energy consumption and network performance implosion due to interference and signaling overhead.

In fact, interference due to uncoordinated resource sharing techniques represents a key limiting factor in the design of dense wireless networks, where resources are limited due to either the costs for licensed bands or the proliferation of hot spots in license-exempt bands. This situation calls for the deployment of *network controllers* with either *local* or *regional* scope, with the aim of orchestrating the access to wireless and backhaul resources of the various wireless network elements.

Moreover, mobility management plays a key role in dense environments, where mobiles can easily undergo several handovers during the same connectivity session. Therefore, there is a need to define novel mobility management mechanisms that are both distributed and offered dynamically. They should be distributed in order to avoid any network bottleneck or single point of failure, and to provide better reliability. They should be activated/deactivated dynamically as needed, in order to globally reduce their signaling load and to increase the achieved performances.

In this paper we present an architecture that tackles the two key challenges highlighted above: interference and mobility management in wireless dense networks. Furthermore, we show that a SDN-based networking approach can be suitably adopted to design the next generation of dense wireless mobile networks.

Regarding interference, in the context of small dense cells, research have shown that simply measuring performance via bit error rate, SINR distributions, or spectral efficiency directly, is no longer very relevant. Instead, rate distribution (user-perceived, i.e., accounting for load) or area spectral efficiency becomes relevant [3]. Therefore, smart cell association policies for dense networks should be based on *user-perceived* rates rather than Base Station (BS) signal strength. Moreover, the seminal work of Knopp and Humblet [4] showed that throughput performance can leverage the presence of time-variable interference conditions by utilizing the wireless medium in an opportunistic way. As a matter of fact, dense wireless deployments show the characteristics typically needed to fully exploit opportunistic gain, especially when network heterogeneity comes into play (e.g., irregular deployments of heterogeneous infrastructures elements including, micro, pico and femtocells are common and have been studied for cellular networks deployment [5], [6]).

Regarding Mobility Management, current IP mobility management solutions pose the following problems [7], which are exacerbated in dense networks: *sub-optimal routing*, since typical solutions rely on a central entity to forward packets to the current location of the terminal, hence providing paths that are generally longer than the direct path between the terminal and its communication peer; *scalability problems*, because existing mobile networks have to be dimensioned to support all the traffic traversing the central anchors and *reliability*, since centralized solutions share the problem of being more prone to reliability problems, as the central entity is potentially a single point of failure.

The FP7 project Connectivity management for eneRgy Optimised Wireless Dense networks (CROWD) has the ambitious objectives of tackling the two challenges above in the specific context of extremely dense and heterogeneous wireless networks [8]. It is worth noting that the latter is a very high potential topic, which has been also selected as one of the five macro-scenarios of the future 5G of telecommunications by the FP7 project METIS[1]. To achieve the required level of flexibility and reconfigurability, and at the same time yielding an energy-efficient network infrastructure in both the radio access part and the backhaul, SDN has been recognized as a basic enabler and driver of innovation within the project.

In this paper we report the initial results obtained within CROWD. Specifically, in Section II we describe the proposed functional architecture, along with some example new functions that can be natively supported by the network. Section III proposes an illustration of the novel mobility management procedures defined so far in CROWD. Conclusions are drawn in Section IV.

II. Network model and control functions

We now describe the network model and network architecture proposed in CROWD. The goal of the proposed architecture is to leverage the heterogeneity of dense wireless deployments, both in terms of radio condition and non-homogeneous technologies. Specifically, the CROWD architecture offers the tools to orchestrate the network elements in a way that intra-system interference is mitigated, channel opportunistic transmission/reception techniques can be enabled, and energy efficiency can be boosted. Furthermore, as detailed in Section III, the architecture accounts for innovative mobility management mechanisms.

As illustrated in the bottom part of Fig. 1, an extremely dense and heterogeneous network consists of two domains of (physical) network elements: backhaul and Radio Access Network (RAN). The latter is expected to become increasingly heterogeneous in the next years in terms of technologies (e.g., 3G, LTE, WiFi), cell ranges (e.g., macro-/pico-/femto-cells), and density levels (e.g., from macro-cell BS coverage in underpopulated areas to several tens or hundreds of potentially reachable BSs in hot spots). Such heterogeneity also creates high variability over time due to statistical multiplexing, mobility of users, and variable-rate applications (chiefly video streaming). Therefore, to achieve optimal performance at all locations at any time, reconfiguration of the network elements is required at all time scales, from very fast (i.e., order of ms to account for, e.g., indoor fading effects) to relatively long (i.e., order of hours to follow mobility patterns, e.g., commuting of citizens between work places and residential areas). This equally affects both the backhaul and the RAN.

We propose to tackle this issue by following an SDN-based approach to network control: the logic for network optimisation is delegated from the network elements to a set of *controllers*, which are virtual entities deployed dynamically over the physical devices depending (among the others) on the actual network load and the capacity constraints. These controllers are technology-agnostic and vendor-independent, which allows full exploitation of the diversity of deployment/equipment characteristics. Furthermore, they expose a so-called Northbound interface, which is an open Application Programming Interface (API) to the control applications. The Northbound interface does not need be concerned on either the details of the acquisition of the data from the network or the enforcement of decisions made. Instead, a Southbound interface is responsible for managing the interaction between controllers and network elements.

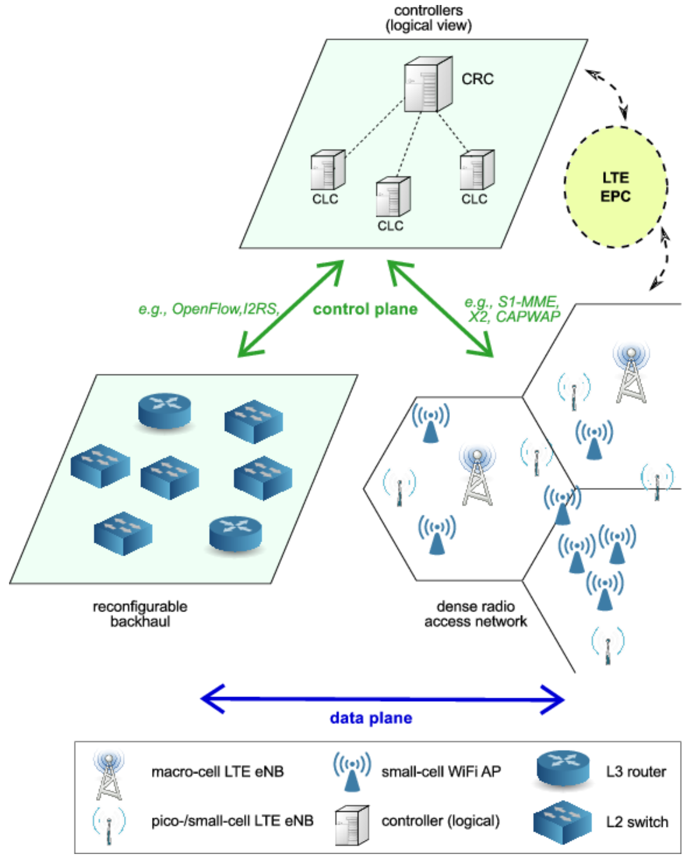


Fig. 1. Network control architecture.

The control plane is shown in the top part of Fig. 1. As can be seen, two types of controllers are indicated: the CROWD Regional Controller (CRC), which is a logically centralised entity that executes long-term optimisations, and the CROWD Local Controller (CLC), which runs short-term optimisations. The CRC only requires aggregate data from the network, and it is in charge of the dynamic deployment and life cycle management of the CLCs, which require detailed and instantaneous data from the network. For this reason, CLCs only cover a limited number of BSs (called a *district* according to the CROWD project terminology).

The CLC can be hosted by a backhaul/RAN node itself, e.g., a macro-cell BS, so as to keep the fast optimisation intelligence to the edge of the network. On the other hand, the CRC is likely to run on dedicated hardware in some network operator data centre.

In Table I we report some key control applications that

[1] https://www.metis2020.com/.

TABLE I
EXAMPLE CONTROL APPLICATIONS.

Names	Objective	Description
LTE interference mitigation	Increased capacity	Dynamically reduce the downlink and uplink interference in a district with multiple tiers of LTE eNBs (macro-/pico-/femto-) via the adaptation of the ABSF patterns, based on the channel quality reports sent by the UEs (downlink) and on the physical measurements taken by the eNBs (uplink), as well as on the current traffic load and QoS constraints, if any.
WLAN optimisation	Increased capacity	Dynamically adapt some configuration parameters of the IEEE 802.11 access points, namely the transmission power and the medium access parameters (AIFS, CWmin, CWmax, TXOPmax) on a per-station basis, depending on the current load of access points, the current transmission rates of stations, and other PHY/MAC layer measurements available at the access points (e.g., retransmissions per station, SINR).
LTE access selection	Increased capacity or energy efficiency	Dynamically associate UEs to one of the LTE eNBs (macro-/pico-/femto-) in a district so as maximise either the capacity or the energy efficiency, under the constraints imposed by the backhaul network. Energy efficiency is achieved by aggregating UEs into as few eNBs as possible (and also possibly selecting those eNBs which are connected to the same backhaul network elements) so that unused devices can be switched off.
Power cycling	Energy efficiency	Periodic reconfiguration of the power cycling pattern of base stations, access points, and backhaul network elements to minimise energy consumption, based on the estimated utilisation and traffic load and/or based on a resource-on-demand availability paradigm.
Offloading	Increased capacity	Dynamic selection of best path, also including point of access selection, for a given traffic flow to maximise network capacity. Downlink and uplink traffic can use different points of access (e.g., uplink goes via the femto-cell eNB or 802.11 access point, while downlink is routed through the macro-cell eNB). Best path selection is made based on QoS and load balancing constraints.

have been identified in CROWD, which are enabled by the proposed network architecture. The control applications described in the table offer a sample of the wide spectrum of applications and technologies that can be targeted by means of SDN-based controllers. Specifically, the proposed control applications range from interference mitigation in LTE, using a multi-tier scheduling scheme among neighbor base stations, e.g., adopting the Almost Blank Sub-Frame (ABSF) paradigm, to innovative LTE access selection schemes, with association and re-association mechanisms that consider energy efficiency in addition to user Quality of Service (QoS). CROWD also targets the optimization of WLANs, which is achieved by fine tuning MAC/PHY parameters of access points and stations on a per-node basis. Since energy efficiency is fundamental for operators and for environmental issues, CROWD proposes, among others, a *Power cycling* control application, to dynamically reconfigure the network and the status of network nodes according to traffic demands. Eventually, CROWD proposes control applications for networks consisting of both LTE and 802.11 devices, e.g., the *Offloading* control application envisions the utilization of load balancing and relay techniques that span across multiple RATs and multiple technologies. The CROWD vision aims at providing a common set of functions as a Southbound interface which can be used by the control applications to build a new set of services such as the ones explained above. For example, in order to fulfil the Southbound requirements of the *WLAN Optimisation* function in Table I, we are studying possible extensions to the CAPWAP [9] protocol to carry the required commands and parameters to the 802.11 access point. Before discussing alternative approaches currently available and under study, we next show that an interesting business process can be built on top of the architecture proposed in CROWD and described above.

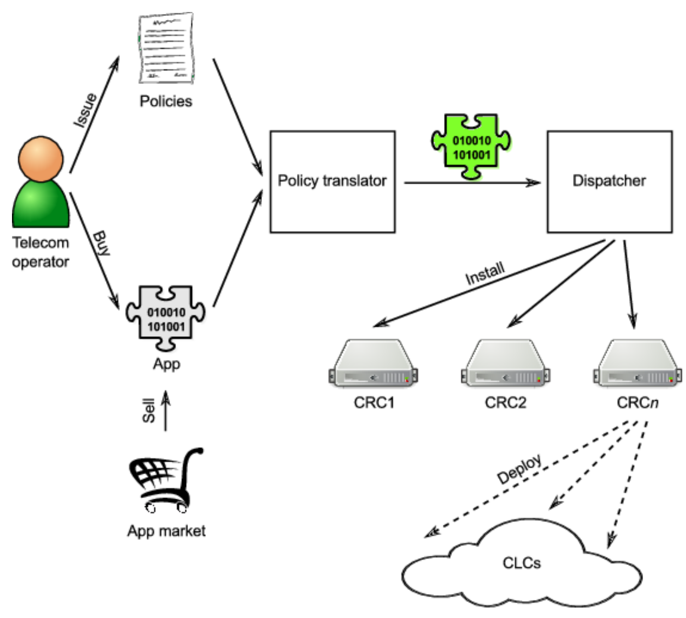


Fig. 2. High-level business process.

A. High-level business process

As illustrated in Fig. 2, the CROWD approach enables the creation of a market of control applications developed by third-party service providers. The telecom operator can buy such control applications (flexible billing models could be also exploited, as inspired from cloud computing business models) and has to define a set of high-level policies which it wants to enforce on its network, or part thereof. For instance, the operator aims to maximise energy efficiency while the network is lightly loaded or to maximize capacity by favoring users with a high bit-rate, while guaranteeing others with a minimum level of QoS even at high loads. The control application and the policies are passed as input to a *policy translator* which configures the control application at a low level based on the high-level objectives expressed by the telecom operator. A *dispatcher* then installs the configured application on all the CRCs of the telecom operators' network. Each CRC dynamically partitions its network in a number of *districts*, deploying one CLC per district, depending on a number of factors, such as processing requirements of the control application (e.g., a complex application will require smaller districts otherwise the computation time would be too high for the optimisation to be effective), number of mobile devices and their QoS requirements and actual traffic (e.g., lightly loaded network may consist of larger districts, in terms of the number of base stations, compared to heavily loaded networks), backhaul characteristics and constraints (e.g., a backhaul bottleneck may suggest the creation of small districts, in terms of the number of base stations, to mitigate the performance penalty due to the controller signalling overhead). In general, more than one application can be in use within the same region/network.

B. Alternative approaches

We now review some alternative approaches, in a mature or emergent phase, which tackles similar architectural issues as CROWD, also clarifying the differences and synergies with the approach proposed in this project.

Operations Support Systems (OSSs) and their evolutions, e.g., UniverSelf[2] and SEMAFOUR[3]: OSSs deal with long-term optimisations of the network and are often integrated with a Business Support System (BSS) handling, e.g, billing data. Regardless of their actual implementation, which can be centralised or distributed, the goal is to take decisions based on high volumes of data which have a statistical, not instantaneous, meaning. Near-real-time services are also possible, but only for fault management via an integrated Network Management System (NMS) and based on pre-configured procedures. CROWD complements OSS since it provides short-term optimisations which react in real-time to the instantaneous changes to network usage. A closed-loop between OSS/BSS and CROWD is possible at a high level, by means of the policy translation function identified above.

Cloud Radio Access Network (C-RAN), e.g., iJoin[4]: C-RAN refers to the centralisation of digital signal processing into a dedicated server within the RAN, which then distributes the digital I/Q signal samples, e.g., via a Common Public Radio Interface (CPRI) bus or the Open Base Station Architecture Initiative (OBSAI) protocol. While this approach brings undoubtful performance advantages due to the enormous flexibility introduced, it requires a significant restructuring of the overall network, which is only justified for macro-cell base stations serving a high number of users. On the other hand, in CROWD we focus on wireless dense networks only, for which the most critical factor impacting penetration is the cost of backhaul improvement. Since backhaul demands in C-RAN are significantly higher than with traditional broadband mobile systems, we argue that C-RAN scenarios are different and non overlapping with the CROWD scenario, while there is not limitations in including C-RAN as part of the CROWD optimisations, at least for macro-cells.

Mobile cloud networking, e.g., MCN[5], TROPIC[6]: the efficient execution of cloud computing applications in a mobile network has unique requirements. Mobile cloud networking refers to the re-engineering of mobile architectures in order to support the efficient and elastic use of network resource, for example, by shifting the mobile network entities (e.g. BBUs (Base Band Units), RRHs (Remote Radio Heads), MME (Mobility Management Entity), etc.) into cloud platform, the network resources can be easily provision and optimize based on the demand. Since CROWD deals with the optimization of the network functions themselves, it does not represent an alternative to mobile cloud network solutions. Rather, the latter, when an in mature stage of development, could be integrated within CROWD as further optimization opportunities.

Self Optimising Network (SON): SON is a generic term referring to the "autonomic" execution of configuration/optimisation procedures at the base stations of a wireless networks, as an alternative to the traditional approach of manually tuning the values of parameters to achieve a given objective function. SON is seen as a basic enabler of large scale deployments of small cells, due to the prohibitive costs which would be incurred by planning, configuration, and optimisation if done manually for the many BSs in the network. SON is typically sold to telecom operators as a proprietary add-on, and it can only be used effectively in a given area if the hardware has been provided by the same manufacturer. While there are attempts to standardise SON, e.g., the X2 interface in LTE and the recently founded OSSII[7] alliance, such attempts are in their infancy. In CROWD we push the SON concept to the next step by proposing a open, i.e., vendor-neutral, architecture which provides a clean abstraction and network control functions via a set of APIs, which are then realised via the Southbound interface in an SDN approach.

III. Mobility functions and protocols

This section is devoted to the detailed analysis of one of the control applications defined in CROWD, the Mobility Management function, since it is one of the controller functions which

[2]http://www.univerself-project.eu/
[3]http://fp7-semafour.eu/
[4]http://www.ict-ijoin.eu/
[5]http://mobile-cloud-networking.eu/.
[6]http://www.ict-tropic.eu/.
[7]http://www.ossii.info/

highly affects the underlying architecture. The solution follows current trends towards distributed mobility management.

We first introduce Distributed Mobility Management (DMM), and then describe the SDN-based DMM implementation proposed in CROWD.

A. The DMM paradigm

Current networks architectures are deployed in a hierarchical manner, relying on a centralized gateway. Thus, the existing IP mobility management protocols are generally deployed following the same pattern. All the data traffic passes through a centralized mobility anchor, such as the Home Agent in Mobile IPv6 or the Localized Mobility Anchor in Proxy Mobile IPv6, and all the bindings are managed at this anchor as well. As the number of mobile nodes and the volume of the mobile data traffic increase, such centralized architectures may encounter several issues already discussed in Section I. In addition, existing IP mobility protocols are designed to be always active, managing all the services and all the traffic in the same way. They do not take into account that mobile nodes may not move during service session (which is 60% of the cases in operational networks [10]) or that a service may not require mobility functions at all. Such approaches may thus lead to non-optimal routing and large overhead due to tunneling mechanisms.

In contrast, novel flat IP architectures are now emerging, requiring the adaptation of current IP mobility management protocols to the evolution of the network. Indeed, there is a need to define novel mobility management mechanisms that are both distributed, to avoid bottlenecks, and offered dynamically, to globally reduce their signaling load and to increase the achieved performance.

Accordingly, the IETF chartered the DMM working group [11] in 2012. Efforts, from both industry and academia, are being performed on specifying DMM schemes, e.g., [12]–[15]. A common feature between different DMM schemes is the distribution of the mobility anchoring at access router level. Mobile nodes change dynamically their mobility anchor for new sessions, while keeping the previous anchors of ongoing sessions. When the sessions attached at a specific mobility anchor are terminated, mobile nodes deregister from that anchor. Assuming that most of the sessions are relatively short, most of the data traffic is routed optimally without tunneling [16].

One of the DMM requirements is to rely on the existing IP mobility protocols by extending and adapting them [7]. This is in order to benefit such standardized protocols before specifying new ones, and also to facilitate the migration of networks architectures. Accordingly, current DMM proposals in the literature focus on being MIPv6-based or PMIPv6-based as it is the general trend in IETF. However, we need to adapt the DMM concepts to our architecture that is SDN-based. Therefore, we propose an SDN-based DMM approach. It inherits some of the PMIPv6 concepts, being network-based and providing local mobility support for mobile nodes moving in a single operational domain, but in addition it splits the control and data planes providing the network with more flexibility in decision making. Hereafter, we discuss the approach and protocol operation in more details.

B. SDN-based DMM solution proposed in CROWD

The SDN solution proposed by CROWD for DMM relies on two main entities, the CLC and the CRC. Since the solution works at layer 3, it is required the definition of new APIs to control the IP layer configuration of the terminal's session anchor point (DMM-GW). Specifically, we need two new APIs: one to convey information on the mobile node to the CRC, such as the IPv6 prefix and DMM-GW assigned to it, and a second one to configure the IP layer of the DMM-GW, the prefixes reachable through the interfaces and to setup an IP-in-IP tunnel (which acts as a Southbound interface). Fig. 3(a), shows the initial attachment phase of the CROWD inter-district mobility solution. The attachment to the network begins by the terminal $MN1$ associating to a point of attachment belonging to the district. This event triggers the sending of an Logical Link Control (LLC) frame by the Access Point (AP), which is encapsulated in an OpenFlow message and forwarded to CLC_1. Through this message, CLC_1 is able to check on its local Binding Cache (BC) whether the mobile node $MN1$ is already attached to the district. If it is not the case, then it will contact the CRC, in order to check if the node is already registered in a previous district, and inter-district mobility is required. In the example depicted in Fig. 3(a), the terminal has not been attached previously to any CROWD network, so CLC_1 is free to assign it any of the available IPv6 prefixes on the district. Once the CLC has decided the prefix and DMM-GW to be assigned to the terminal, it proceeds to install the prefix in the DMM-GW ($DMM\ GW_1$). In this way, the CLC has an extra degree of flexibility, being able to assign arbitrarily the prefix to the selected gateway[8]. In addition, prefix, DMM-GW and terminal identification (e.g., MAC address) are notified to the CRC, that is able to keep track in this way of the previous attachments of the terminal.

Afterwards, the standard procedure followed by a terminal after successful attachment to a new network is performed. It includes the sending of a Router Solicitation (RS), in order to configure its IP address using IPv6 Stateless Auto-Configuration (SLAC). As in the case of the LLC message, the network encapsulates the RS message and sends it to the CLC. The CLC uses a Router Advertisement (RA) message to answer the RS, providing the prefix and default router ($DMM\ GW_1$) selected before. Hence, through the mediation of the CLC, highjacking the RA functionality of the network, we are able to control the IP level attachment of the terminal within the CROWD network. At this point in time, the CLC is able to compute the match rules and data path modifications required to forward the terminal's packets to the selected DMM-GW. These modifications are configured into the network through the OpenFlow protocol, requiring several message exchanges among CLC_1 and the different switches conforming

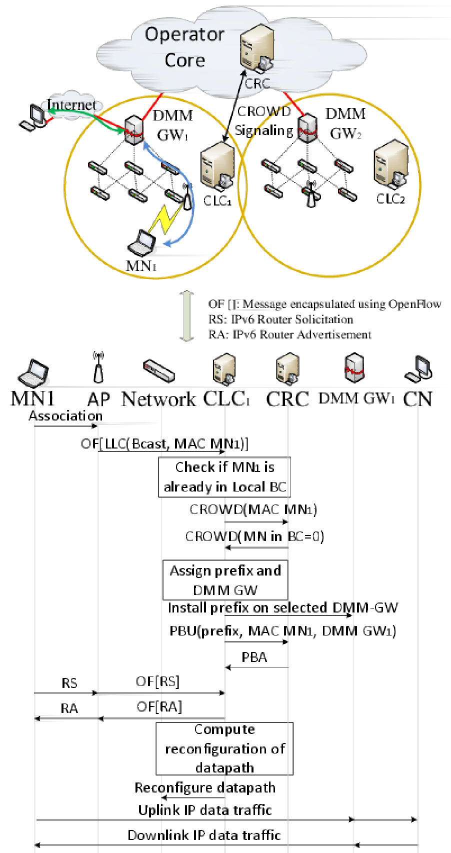
[8]Subject to the routing constraints imposed by the operator.

the path between the terminal and $DMM\ GW_1$. Once the data path is configured, packet originated at the terminal with layer 2 destination the DMM-GW, are transparently forwarded at layer 2. This behaviour is completely transparent to the layer 3 stack of the terminal, which sees the path between the terminal and the DMM-GW as a single hop.

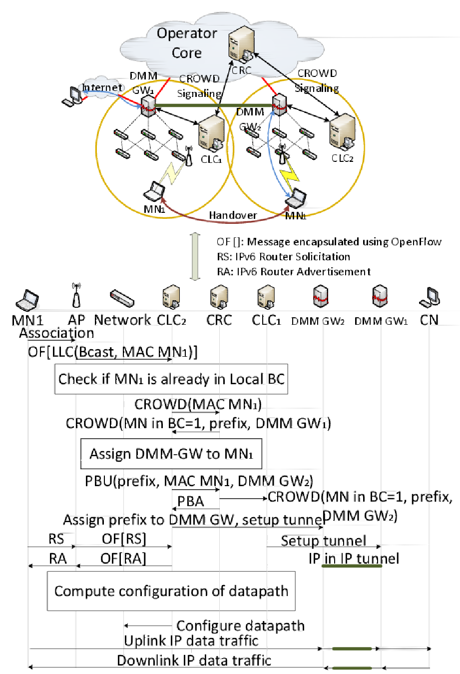
Fig. 3(b) presents the procedure of a handover between two different CROWD districts. The procedure assumes that the initial attachment process has been carried on as presented above. The procedure relies on the communication among the CLCs being orchestrated by the CRC. Basically, the CRC behaves as a data-base containing the list of previous DMM-GWs to be considered while performing handover. The configuration of the IP layer on the DMM-GWs and the tunnel setup among them is handled locally by the CLCs on each district. The procedure starts when the terminal attaches to an access point in a different district. As in previous cases, this event triggers the CLC (CLC_2) to check if the node is registered on its internal BC. As this is the first time the terminal attaches to the district, the CLC asks the CRC for previous registrations. In this case, the CRC has information regarding the terminal, informing the CLC of the prior connection of the terminal to $DMM\ GW_1$ and the prefix used. With this information, CLC_2 is able to decide the DMM-GW ($DMM\ GW_2$) to be used within this district and informs the CRC of this information. The CRC stores this information on its local BC for future reference. At this point in time several procedures are performed in parallel. First, the CRC informs CLC_1 of the new location of terminal $MN1$. With this information, CLC_1 configures $DMM\ GW_1$ with an IP-in-IP tunnel connection to $DMM\ GW_2$ and changes the routes at $DMM\ GW_1$ so that the prefix used by the terminal is routed through the tunnel. In parallel, CLC_2 configures the new prefix in $DMM\ GW_2$ and setups the IP-in-IP tunnel towards $DMM\ GW_1$. Once the tunnel is established, the configuration of the data path in the new network is performed as in previous cases. When all the procedure is complete, packets from the core network CN to terminal $MN1$ are forwarded first to $DMM\ GW_1$, which tunnels them to $DMM\ GW_2$. After $DMM\ GW_2$, the OpenFlow configured data path takes care of forwarding the packets to the appropriate location of $MN1$ within the district.

IV. Conclusion

In this paper we have introduced an approach based on SDN for the efficient and scalable realisation of control functions in extremely dense and heterogeneous wireless networks, as identified as part of the preliminary results in the FP7 project CROWD. First, we have illustrated the general network model, also including a critical review of the possible alternative solutions put forward in the market and within the research community, as well as a long-term business process supporting the paradigm envisioned. Second, we have focused on the issue of efficient and scalable mobility management, which is of paramount importance in the use case of interest mentioned above.



(a) Initial attachment.



(b) Inter-district Mobility: Handover.

Fig. 3. Inter-district Mobility procedures.

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