Virtual Radio – A Framework for Configurable Radio Networks

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ABSTRACT

Network virtualization has recently been proposed for the development of large scale experimental networks, but also as design principle for a Future Internet. In this paper we describe the background to network virtualization and extend this concept into the wireless domain, which we denote as *radio virtualization*. With radio virtualization different virtual radio networks can operate on top of a common shared infrastructure and share the same radio resources. We present how this radio resource sharing can be performed efficiently without interference between the different virtual radio networks. Further we discuss how radio transmission functionality can be configured. Radio virtualization provides flexibility in the design and deployment of new wireless networking concepts. It allows customization of radio networks for dedicated networking services at reduced deployment costs.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: *distributed networks, network topology, wireless communications*, C.2.2 [Network Protocols]: *Protocol architecture*, C.2.3 [Network Operations]: *Network management,* C.2.5 [Local and Wide-Area Networks]: *Access schemes*

General Terms

Design, Management

Keywords

Network virtualization, Configurable radio networks, Future Internet

1. INTRODUCTION

A number of research initiatives around the globe are developing designs for a Future Internet; the objective is to overcome fundamental problems of the current Internet. One of those problems is the stagnation of technical evolution of networking functions; *network virtualization* is proposed as a solution to overcome this problem. The number of wireless end devices is already now orders of magnitude larger than the number of fixed Internet hosts; the Future Internet will comprise a large number of wireless networks, which will primarily be connected at the edges. Any Future Internet design will need to take these wireless networks into account. In this paper we investigate how the concept of network virtualization can be extended to the wireless edge. Even more, we discuss how radio network virtualization can be used to accelerate the innovation cycle of radio networks and how it can be used for reducing the deployment costs.

In section 2 we list some deficiencies of innovation in radio networks and present related work in section 3. Our radio virtualization concept is described in section 4, followed by a discussion and conclusion.

2. DEFICIENCIES FOR TECHNICAL EVOLUTION OF RADIO NETWORKS

A tremendous amount of effort is spent on the research of wireless transmission and new concepts are continuously developed. A non-exclusive list of examples of such technical concepts comprises:

- smart antenna solutions (MIMO, beamforming, space-division multiple access),
- new channel coding schemes,
- cooperative transmission schemes (e.g. network MIMO, inter-cell interference coordination),
- improved radio link protocols, scheduling disciplines and QoS aware transmission methods,
- relaying, multi-hop transmission, mesh networking and routing,
- new mobility management protocols (e.g. proxy mobile IP, fast mobile IP, context transfer),
- integration of multicast transmission.

Despite the technical progress, it requires a significant amount of time before such technical concepts are integrated into real-life operational radio networks, if at all. A faster technical evolution of capabilities in radio networks could accelerate the development of wireless communications services and applications. To make a comparison with another technical area: the continuous evolution of the integration density of integrated circuits – following Moore's law – leads to a growth of computing performance that spurs the development of new software applications. In the wireless industry, in contrast, the evolution of radio networks tends to be slower than the development cycles of new data applications and services. As a result, the implementation and deployment of advancements in wireless network realizations sometimes lags behind the development of the concepts. We propose to use radio virtualization to accelerate the evolution process and increase the flexibility of radio network infrastructure in order to bring more innovation into radio networks.

In the following we describe two major reasons for the slow pace of evolution in wireless networks.

2.1 Long Development Cycles

Wireless communications systems are complex in nature; a significant amount of research is required to understand the behavior and characteristics of technical concepts before they can be applied in real systems. But it is not sufficient to develop and understand new technical solutions. As different components of wireless communication systems are typically provided by a large number of different vendors, and further these systems are targeted to be used on a global basis, extensive coordination between all involved players is required. This is achieved by standardization: different players worldwide develop in a consensus-building process a specification of system components and functions so that the components of different vendors can be combined in an interoperable manner. One particular complication is the need to ensure that a new technical feature is compatible with other already existing features. A migration strategy always needs to be considered when features are introduced which are not immediately supported by other components. In some cases the technical solution to ensure the backward compatibility of a new feature can be more complex than the new feature itself. The standardization process and the subsequent conformance testing consume a considerable amount of time.

In addition to the duration of the standardization process, further delay in the market introduction of new functionality is caused by the actual deployment. Public wireless communication networks are typically very large, e.g. they provide service over an entire country. The introduction of a new technical feature into such a network – or the build-out of a new network – simply requires a substantial amount of time.

A reduction of the market introduction time of technological advancements is of great benefit to the operator. The approach of radio virtualization can achieve this by making radio networks shareable and reconfigurable. In this way new features can be more easily introduced into existing networks by reconfiguration rather than replacement. Further, we wish to enable a gradual and experimental deployment of new features, as well as avoid unwanted interactions with existing features. This helps to reduce the level of consensus that is required in the standardization process. As a result, new features can be more quickly introduced – e.g. for experimental purposes – and possibly be further refined in an iterative manner.

2.2 Economic Barriers

The introduction of new functionality into wireless communication networks is also hampered by economic considerations. Apart from the costs implied by the development process, the infrastructure costs of a radio network – with all its base station sites, antennas, radio control nodes and fixed and wireless interconnection links – is one of the largest cost components within a cellular network. Any build-out of the radio network with new functionality requires long-term planning and large up-front investment. Such an investment can only be motivated if a significant shortage of resources is noticed, or a large demand for a feature can be anticipated. This is further intensified by the fact that a transmission network (including the wireless access) increasingly plays the role of a pure bit pipe in the value chain of an operator. An added value of new functionality can only be gained if the addition of a feature leads to traffic growth or reduces investment or operation costs.

With our novel approach of radio virtualization we aim to lower this economic barrier of entry for the deployment of new technologies. This is achieved by adding increased flexibility and reconfigurability to ease the introduction of new features, and by allowing different players to share infrastructure costs by enabling them to deploy their different technical solutions in parallel on shared infrastructure. New technical realizations can be implemented by re-using existing infrastructure, thereby reducing introduction costs.

3. RELATED WORK

The concept of virtualization of communication networks is recently being considered as an architectural approach for the design of the Future Internet [1][2][3][4][5]. It has been observed that new technical concepts – even if well understood and standardized – are hardly being introduced into the core Internet design anymore [6]. This phenomenon is known as *ossification of the Internet*. It has also been claimed that there is no single best design for the Future Internet [1][7] – different solutions for different scenarios can be superior. The concept of *network virtualization* provides the basis for an architecture that enables the deployment of multiple network architecture solutions on top of a common network infrastructure. Network virtualization utilizes two well known concepts. The separation and isolation of different types of traffic on transmission links is known from *virtual private network* (VPN) technologies. Furthermore, virtualization technologies that are today used on computing platforms to implement logically separate *virtual machines* on the same physical hardware resources, such as e.g. XEN [8] or VMware [9], can also be utilized to virtualize active network nodes such as routers.. A distinctly different approach for establishing logical network architectures with specific functionalities are overlay networks (see e.g. [10]). Overlay networks are easily configurable by establishing required functionality on dedicated overlay nodes. Also network virtualization concepts have been proposed as a method to create overlay networks (e.g. [11]), for example to enable experimental testbeds on existing infrastructure [12] [13]. However, overlay networks are decoupled from the physical resources. The characteristics of physical transmission cannot be adapted to the needs of the overlay application. The connectivity and transmission characteristics are determined by active probing; this results in inefficient and imprecise methods for discovery and observation of transmission resources – which is in particular unsuitable in wireless networks which have limited radio resources and battery resources of mobile devices. What we denote as *network virtualization*, in contrast, provides configurability involving direct interaction with physical resources. It enables innovation to happen in the network close to network resource management functions, rather than in an application level overlay. The use of network virtualization in the context of network experimentation is described e.g. in [3][14] [15]. Based on a common network infrastructure (denoted as substrate) a number of virtual networks can be created. For each virtual network the following properties need to be determined:

- The subset of nodes and links of the substrate that are part of the virtual network,
- The functions and communication protocols that are used on the participating nodes,
- The amount of resources allocated to the virtual network on the participating links and nodes.

A systematic approach to network virtualization requires a comprehensive *virtualization management* framework. This comprises the discovery of resources along with their capacities, capabilities and locations; the determination of a suitable virtual network topology connecting the nodes and links that should be part of the virtual network; and finally, the instantiation of the virtual network by allocating resources in the participating nodes and links, configuring the desired functionalities (e.g. by downloading custom protocol stacks), and establishing connectivity. Once the virtual network is instantiated, additional management operations may be necessary to re-allocate, add, remove, or reconfigure resources as required.

The application of virtualization for wireless networks, with some focus on WLAN technologies, is discussed in [16] – as wireless extension to the GENI experimental framework [15]. The goal of [16] is to provide multiple concurrent experiments on wireless testbeds, where isolation is e.g. achieved by spatial separation. In our approach virtual radio networks are pursued to provide independent operational networks on shared infrastructure, where the topology, and capacity is determined by the expected traffic distribution of the end users of the different virtual networks.

The general concept of network virtualization, as well as our specific solution of radio virtualization, is based on sharing network infrastructure. In 3G wireless networks sharing of network infrastructure is already applied (denoted as *network sharing* [17][18]) in order to reduce network deployment costs. There is a substantial difference between network sharing in 3G networks and radio network virtualization. In 3G systems network sharing is used to allow multiple operators running services over the same infrastructure; the network functions are identical (as defined by the 3G specifications) for all operators. In our virtual radio approach we allow different types of functionality being used in different virtual radio networks running on top of the same infrastructure.

A significant amount of research has investigated re-configurability of radio access functions. The main focus has been on the configurability of physical layer functions (often referred to as *software-defined radio*), which allows using the same hardware and software components for the transmission via different radio access technology standards. An overview is provided in [19][20]. Considerably less work has been put on the configuration of radio protocol and radio network management functionality. The definition of a generic link layer, which is configurable for multiple radio access technologies, has been proposed in [21][22][23]. Similar work on a generic protocol stack has been developed in [24][25]. An object-oriented approach to configuration of a generic protocol stack is described in [26]. The configuration of radio protocol functions based on composition of so-called *functional units* has been proposed in [27][28]; similar protocol configuration methods have been described in a more general context in [29] but also in early work on modular and efficient protocol implementation [30][31]. A reconfiguration management plane for reconfigurable networks has been developed in [32]. It differs from virtual radio networks in that it reconfigures an entire infrastructure, whereas radio virtualization provides independent reconfigurability of each virtual radio network running on the shared physical infrastructure.

4. VIRTUAL RADIO CONCEPT

The provisioning of a multitude of virtual networks with wireless radio links requires the capability to share radio resources while at the same time avoiding interference between the different virtual radio networks. Our approach to this problem is to realize the virtual networks on a commonly shared physical network infrastructure. We assume that a physical network infrastructure is available and provided by an infrastructure provider; sufficient dimensioning of the availability and capacity of the infrastructure could be achieved based on a demand-driven build-out (e.g. according to the requests of one or more virtual network operators) and/or based on regulatory policies. The infrastructure nodes are then responsible for the resource sharing and interference avoidance between the virtual radio networks. The process of sharing and allocating resources belonging to a physical radio link (i.e. a radio resource) we refer to as *radio virtualization*; the resources that are used by a particular virtual network node we refer to as *virtual radio* (i.e. a virtual link). The virtual instantiation of node functionality running on a physical network node we call *virtual node* (VN). The coordination and management of physical resource allocation among a multitude of virtual radio nodes is performed by a *resource allocation control* (RAC) function. A virtual network consists of a set of links and nodes; by *virtual radio network* we refer to a virtual network in an edge network of the Future Internet that comprises multiple inter-connected virtual radio nodes.

4.1 Virtual Radio Networks

The deployment of a virtual radio network is performed in several steps. An infrastructure owner provides a configurable network infrastructure. Every network node can comprise multiple virtual nodes; the management of those virtual nodes is performed by a *virtualization manager* as depicted in Fig. 1. The virtualization manager announces (step ⓿) the capabilities, as well as the availability of node and link resources to any interested virtual network operator via a virtualization management interface (VMI). This can e.g. be realized by posting an offer on a public resource exchange. A virtual network operator is an entity that desires to deploy a virtual network. If it wants to include a node into a virtual network, it contacts the virtualization manager of this node and initiates a negotiation process. The negotiation (steps ❶-❷) comprises the assignment of resources, and optionally also usage policies and pricing. If the negotiation is successful and the virtual network operator accepts the offer (step ❸) the virtualization manager instantiates a new virtual node with the negotiated properties and grants it to the virtual network operator (Fig. 2 steps ❹-❺). The virtual node behaves as if it was a dedicated node owned by the virtual network operator. In particular, this includes full access allowing the virtual network operator to configure the communication functionality that shall be performed by the node (steps ❻-❼). The virtual node then becomes an active element within the virtual network.

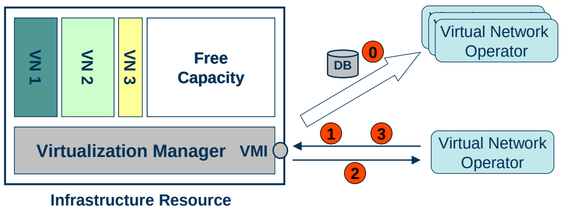

Figure 1. Negotiation of Virtual Network provisioning.

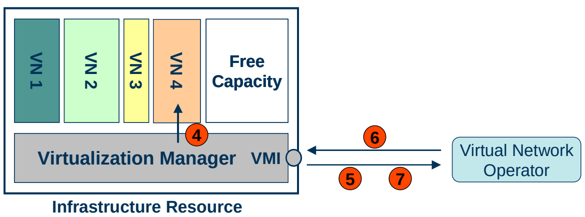

Figure 2. Virtual Network node configuration.

A complete virtual network consists of a number of different nodes. As explained earlier the setup of a virtual network comprises the steps of determining the nodes that are suitable for the desired communication need. Fig. 3 depicts multiple virtual radio networks that are sharing a common infrastructure; different nodes may be part of different virtual networks set-up by different virtual network operators. A virtual network does not only contain infrastructure nodes, but also end-user devices (where end-users can be persons, machines, or sensors/actuators). The largest part of end-user devices in a Future Internet will be wirelessly connected to the network infrastructure. Such mobile terminals can connect to one or more virtual radio networks according to their need. Mobile devices can also be re-configurable to be flexible enough to connect to different virtual radio networks. But also non-configurable devices can exist (e.g. for cost-efficiency) that provide connectivity only to a limited number of specific virtual radio networks.

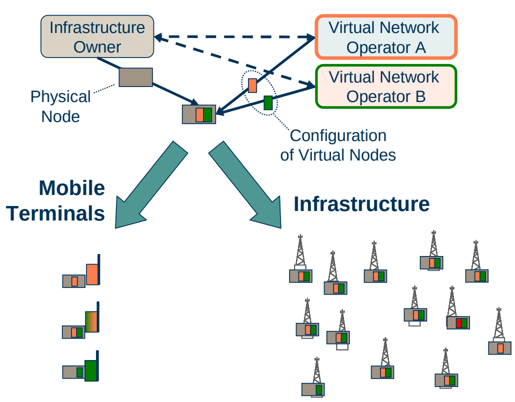

Figure 3. Multiple Virtual Radio Networks consisting of virtual nodes and virtual links.

4.2 Virtual Radio – Radio Resource Sharing

Different virtual radio networks instances on a common node have to share the processing and transmission resources that are available at that node; for wireless links this requires a sharing of the radio resources. The access to the transmission resources are managed according to a multiple access scheme, like code-division (CDMA), time-division (TDMA) or frequency-division (FDMA) multiple access; several multiple access schemes can also be combined. Fig. 4 depicts a generalized partitioning of radio resources in the time, frequency and code domain, where the radio resource blocks are defined by the multiple access scheme(s). A difference to multiple access schemes used in today's wireless networks is that radio resource blocks are allocated to virtual radio networks rather than to individual users. The multiple access between different users of the same virtual radio network are handled separately within each virtual radio network and within the resources that have been allocated to the particular virtual radio network.

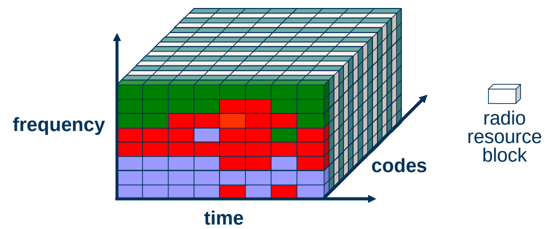

Figure 4. Generalized radio resource partitioning into resource blocks.

In order to avoid interference between transmissions in different virtual radio networks, the access of the different virtual radio nodes to the radio resources is coordinated by a common resource allocation control (RAC) function, as shown in Fig. 5. This means that all virtual radio networks need to have a common compatible partitioning of radio resources into resource blocks according to Fig. 4. Apart from that, different virtual radio nodes can have differently configured protocols and functions for data transmission, virtual-network-internal network management, or virtual-network-internal control and resource management. However, the access to the physical spectrum resource is still provided by the RAC. This central coordination has several benefits: it provides efficient usage of the resources with low overhead and without contention; it avoids interference and collisions between the different virtual radio networks and thus provides a high level of predictability of the resources available to each virtual radio node.

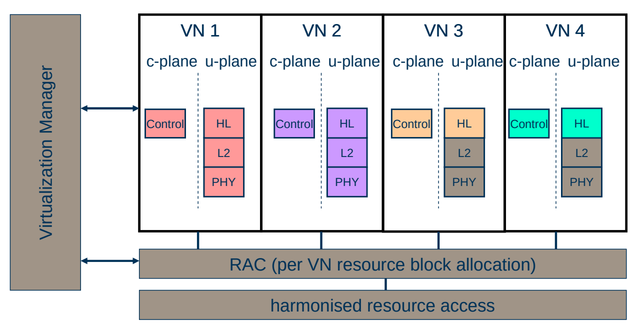

Figure 5. Different virtual nodes sharing the radio resources of the physical node.

4.3 Configuration of Radio Networks

In order to establish the specific functionality of a virtual radio network on a physical node it needs to be configurable. As indicated in Fig. 5, the configuration of transmission methods can span over a wide range of functionality from the physical layer up to higher layer functions and control functions. The only theoretical restriction in configurability is given by the coordinated sharing of the physical resources; this requires to use a common structure of radio resource partitioning for all virtual radio nodes (see Fig. 4) and a coordinated access to radio resource blocks via the resource allocation control function.

Configurable functionality of a virtual radio node can comprise physical layer procedures, such as channel coding, smart antenna management (MIMO, beamforming) or cooperative relaying; it can be link layer functionality, like (hybrid) automatic repeat request (ARQ), space division multiple access (SDMA), header compression schemes, or ciphering; or it can be higher layer functionality such as end-to-end naming schemes, inter-domain gatewaying and routing, network coding and multi-path-routing, network storage, congestion control proxying, application layer adaptation. Apart from data-plane functionality also control functions can be configured per virtual radio node, for example local routing and mobility management (incl. mesh and ad-hoc routing, mobility management optimization and context transfer), radio-resource management and scheduling (within the virtual radio), cross-layer design and optimization, authentication and authorization schemes, as well as battery-saving schemes like discontinuous transmission/reception and sleep modes.

There are different ways for a virtual network operator to program/configure and instantiate such functionality on a virtual node. A physical node can have a library of basic functional units; the virtual network operator can then compose the desired functionality by combining functional units (see e.g. [27], [30]) – possibly allowing some user-defined extensions inherited from base functional units (e.g. [26]). A difficulty is that certain functions have high processing requirements and may require support by dedicated hardware (e.g. ciphering or MIMO). In this case only a limited set of configurable algorithms or procedures can be provided by the physical node, putting some limitation on the degree of configurability. Another approach is to make the virtual node freely programmable and a virtual network operator installs the desired software code. To support specific tasks different types of programmable processing entities can be provided by the physical node, ranging from general purpose processors to configurable logic like FPGAs (see [4]).

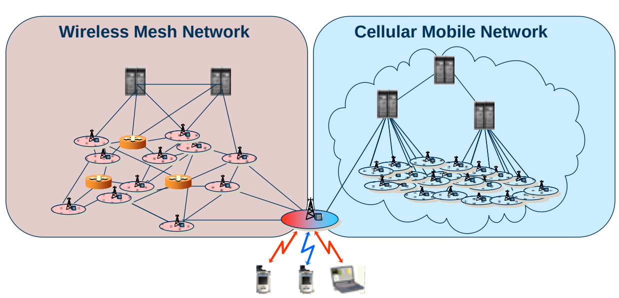

Figure 6. Example of a physical radio node being part of two virtual radio networks.

Fig. 6 shows an example of two virtual radio networks partly sharing the same physical nodes. One radio access node is hereby part of a cellular virtual radio network (e.g. using cellular mobility management schemes), and also a mesh virtual radio network (e.g. using mesh routing possibly combined with network coding and cross-layer optimization). Similarly, one of the virtual radio networks could be a virtual network customized for machine-to-machine communication that shares the same infrastructure; such a virtual network could be optimized for the transfer of a huge number of low traffic data sessions and battery-efficient operation of the end nodes. Example applications for such a virtual network could be industry automation, logistics or vehicular applications.

5. DISCUSSION

The introduction of radio network virtualization can revolutionize the evolution and usage of wireless networks. It enables an acceleration of the innovation cycles of wireless transmission concepts and eases **extensibility and evolution** of wireless networks. It allows for infrastructure sharing, which may allow reducing network deployment costs and thus also the price per transmitted bit. Further, it allows **customization** and **pluralism** of networks: a virtual radio network targeted at machine-to-machine or sensor applications can be adapted to these applications and requirements, while at the same time another virtual radio network is optimized for providing Internet services to mobile users. The flexibility of virtualization provides a means for **migration** from one network design to another. For the new design a new virtual network is created in parallel to the old design. Initially (e.g. when few end users own devices that support the new design) a small amount of resources is allocated to the virtual network of the new design; at a later phase few resources are allocated to the virtual network of the old design, before it is eventually deleted. Similarly, virtual networks can be used for **experimentation** of new radio networks designs, running on real infrastructure yet isolated from other operational virtual networks, and limited in scope but still affordable due to reuse of existing infrastructure.

Apart from technical merits, network virtualization can lead to new **business roles** by separating the operation of the physical infrastructure from the operation of the networking service. This decouples the life cycles of infrastructure build-out and network service deployment; on a given infrastructure a larger variety of customized networks can be provided (limited by the capabilities of the physical nodes and links). This can affect regulatory frameworks and opens up the space for more "tussles" [33]. For example, the build-out of physical infrastructure determines what amount of networking capacity is available at different regions. In an open market situation with separate infrastructure and virtual network providers, infrastructure build-out will only happen where virtual network operators foresee a significant demand and request infrastructure availability. This may lead to regions (like rural areas) where it is economically unfeasible to provide network capacity and networking services. The provision of network infrastructure could then still be provided, e.g. due to a political objective to reduce the digital divide; infrastructure could, for example, be subsidized with taxes or it could even be state-owned[1]. Competition between virtual network operators would then happen only on the basis of the provided networking service.

The concept of network virtualization also has a number of drawbacks. First, virtualization leads per-se to an increased overhead due to the partitioning of resources. On the other hand, this may be compensated by a certain amount of aggregation. For example, instead of a number of separate UMTS operators

[1] This is similar to discussions around public or private ownership of the power grid, the railway system or motorways.

building their own physical network and operating in their licensed frequency band, an infrastructure provider could build a single infrastructure using all UMTS frequency bands. This aggregation would compensate the overhead of partitioning when different virtual radio network operators lease their share of resources. Second, the management of virtualization – including the negotiation and configuration procedures (cf. Figs. 1-2), but also the programmability of physical nodes – still has to prove its scalability and performance. On the other hand, virtualization is increasingly being applied with success in different areas from computing to networking and significant resources are devoted to it. It can be expected that substantial progress in this field will be achieved in the coming years. Third, the customization of virtual networks may lead to a large number of different networks. In particular end devices will for cost and performance reasons often not be fully configurable and instead be dedicated for the use in a particular virtual network. For end devices this may result in loosing economies of scale, leading to higher costs. On the other hand, it can be anticipated that market forces will limit the number of virtual networks to a feasible level. Finally, virtualization may raise some concerns with respect to liability in case that regulatory requirements are associated with networking services. A clear separation of liability of the infrastructure provided functionality and the virtual network provided functionality is desirable. As the virtual node functionality runs in virtualized sandboxes on the physical node, the physical node can provide limits regarding the functionality that the virtual node can effect (e.g. it can prohibit the virtual node from transmitting too high interference into adjacent frequency bands). For some cases (e.g. the reliability for emergency services) it may not be so easy to identify the responsibility for violating requirements or contracts.

6. CONCLUSION

In this paper we have presented the background, motivation and concept of *radio virtualization*, which allows operating different virtual radio networks on a common shared infrastructure. This concept extends virtualization ideas proposed for the Future Internet design into the wireless domain. Radio virtualization provides more flexibility in the design and deployment of new wireless networking concepts. It also allows to customize radio networks for dedicated networking services at reduced deployment costs due to the reuse of existing infrastructure. Radio virtualization will be further developed and evaluated in the new 4WARD project on Future Internet design [34], which is funded within the European 7th framework program.

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