Software Defined Cognitive Radio Network Framework: Design and Evaluation

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***Abstract*—Software defined networking (SDN) provides a novel network resource management framework that overcomes several challenges related to network resources management. On the other hand, Cognitive Radio (CR) technology is a promising paradigm for addressing the spectrum scarcity problem through efficient dynamic spectrum access (DSA). In this paper, we introduce a virtualization based SDN resource management framework for cognitive radio networks (CRNs). The framework uses the concept of multilayer hypervisors for efficient resources allocation. It also introduces a semi-decentralized control scheme that allows the CRN Base Station (BS) to delegate some of the management responsibilities to the network users. The main objective of the proposed framework is to reduce the CR users' reliance on the CRN BS and physical network resources while improving the network performance by reducing the control overhead.**

***Index Terms*— Software Defined Radio, Cognitive Radio Networks, Hypervisors, Resource Virtualization, Resource Allocation, Software Defined Networking, IEEE 802.22 , WRAN.**

I. Introduction

DUE to the low cost and widespread acceptance of the wireless communication devices, the available radio spectrum is becoming insufficient to fulfill the needs of these large numbers of wireless devices. Users of wireless networks are generally viewed as either Primary Users (PUs) or Secondary Users (SUs). PUs are licensed to operate over a licensed spectrum that is reserved for their own services. These reserved spectrum bands are not fully utilized (Bany Salameh and Krunz 2009). So, to improve the spectrum utilization, SUs are allowed to opportunistically access the licensed bands without affecting the performance of the PUs.

Cognitive Radio (CR) is a technology that enables a cognitive radio node (SU) to sense its surrounding environment and change its transmission parameters according to the acquired information with the goal of increasing spectrum utilization. For example, the cognitive Radio Interface (RI) can sense its environment for the available spectrum (spectrum holes) and then divides it into a set of channels and select the best channel that does not cause interference with a PU according to a predefined policy (Bany Salameh 2010).

The IEEE 802.22 standard for Wireless Regional Area Network (WRAN) is the first effort to make commercial applications based on CR technology feasible (Cordeiro et al. 2005, Bany Salameh et al. 2014, Hani et al. 2013, Mhaidat et. Al. 2014). According to IEEE 802.22, a network consists of a BS and a set of users. The available spectrum is divided into orthogonal channels. To provide better knowledge of the availability of channels, the users sense the spectrum availability in their vicinity and periodically send their sensing reports to the BS. The BS acts as a centralized broker governing the users' use of the spectrum. Thus, whenever a user wants to transmit, the BS has to be consulted. Such high overhead of control communication between the users and the BS will surely have a negative impact on the overall performance of the network.

Simplifying network resource configuration and management is a very challenging and complex task. The newly emerged concept of software defined networking (SDN) provides a new paradigm shift in efficiently managing network resources (Kim and Feamster 2013). SDN is receiving an increasing attention from both academic and industrial communities for its promising features. SDN permits network managers to control the network resources with software tools without the need for tedious manual configuration. It promotes the separation between the data plane and the control plane of the network (Costanzo et al. 2012, Li et al. 2012, Hasan et al. 2013).

In this paper, we introduce Software Defined Cognitive Radio Network (SD-CRN) framework. SD-CRN provides a virtualization based resource allocation approach for cognitive radio networks. In our approach, we advocate delegating some of the management responsibilities of the BS to the users allowing them to make local decisions. By doing so, we aim to reduce the users' reliance on the BS and improve network performance by reducing the unneeded control overhead. The resource management process is totally software based without the need for any network administrator interventions. The distinct features/advantages of our work are: (1) the cooperative resource management over wireless cognitive networks, (2) a centralized BS controls and manages the resource allocation using a centralized manager called the

Global Hypervisor (GH) among the different cognitive users joining the network without affecting the PUs, and (3) virtualizing the physical radio nodes to have several instances for different virtual networks, each of which having an intermediate layer called the Local Hypervisor (LH). The LHs support the GH in distributing the resources to minimize the control overhead at the BS. These features/advantages play a significant role in improving the overall network throughput, as well as minimizing the management overhead at the BS (Jararweh et al. 2014, Doulat et al. 2014).

The rest of the paper is organized as follows. The following section contains a brief overview of the literature whereas Section III discusses the proposed SD-CRN framework, which is tested and evaluated in Section IV. The conclusion and future directions of this work are discussed in Section V.

II. RELATED WORKS

The keyword "virtual" was used in the CR literature in several contexts. For example, the authors of (Čabrić et al. 2005) used it in the context of how to use CR technology to re-use allocated (but unused) spectrum. The authors of (Ishibashi et al. 2008) used the virtual concept to define a virtual wireless networks (VWN), which is a network with no physical resources of its own. A VWN provides services to the clients using the resources of other networks in a CR-based fashion.

On the other hand, other works have used the word "virtual" in a more general context. In (Sachs and Baucke 2008), the authors proposed a platform where different virtual radio networks running on top of the physical nodes can share the available spectrum. The access to the spectrum was managed according to a multiple access scheme like CDMA, TDMA or FDMA.

In (Nakauchi et al. 2011), the authors proposed AMPHIBIA, a platform that exploits the network virtualization and cognitive radio technologies while keeping the advantages of each. In AMPHIBIA, a cognitive BS dynamically configures a wireless access network for each virtual network. For each service provider, AMPHIBIA tries to build an independent and configurable virtual network. These virtual networks can be used by the service provider to provide its services for the end users. AMPHIBIA has three main components. The first one is the service provider, which requests a virtual network from AMPHIBIA to provide its services. The second component is the infrastructure provider, which provides the AMPHIBIA with a physical infrastructure that can be used to build multiple virtual networks over it. The last component is the radio terminal, which requests the service provider to provide a service and also provides AMPHIBIA with the corresponding quality of service (QoS).

In a follow-up work (Nakauchi et al. 2012, June), the authors implemented a system prototype for AMPHIBIA including the implementation of a cognitive virtualization manager, which controls the process of network reconfiguration. The authors demonstrated that a virtual machine-based virtual network including a virtual Cognitive BS (vCBS) that can be dynamically established, expanded, and removed and the streaming services can be flexibly deployed on demand on the virtual network. They also showed that AMPHIBIA is capable of creating and reconfiguring vCBSs in a nearly short time interval. They showed the node setup for the virtual cognitive BS, which is hosted on a host BS, and dealt with as a virtual machine. It also contains a node manager and a number of vCBSs. The node manager is responsible of managing the available resources and the access control in the host BS. On the other hand, the node manager has an interface for the network virtualization manager, and initiates and removes the virtual cognitive BSs based on the instructions from the network virtualization manager. Each virtual cognitive BS has all the functionalities of the original cognitive BS, in which it contains a Cognitive BS Reconfiguration Manager (CBSRM), a Cognitive BS Measurement Collector (CBSMC), and Cognitive BS Reconfiguration Controller (CBSRC).

Network virtualization has been widely used in traditional wireless technologies. For example, the authors of (Nakauchi et al. 2012, July), applied network virtualization on a WLAN system adopting the IEEE 802.11e EDCA (Enhanced Distributed Channel Access). The authors focused their study on controlling the air-time usage rather than controlling the bandwidth usage. They proposed an air-time based resource management technique for wireless network virtualization where many virtual networks compete for the available network resources. For each virtual network a dedicated Virtual Access Point (VAP) was created on a physical access point (AP). The VAP enables its corresponding virtual network to reserve and control the required resources on the physical wired network.

The authors of (Zaki et al. 2011, Zhao et al. 2011) proposed to virtualize LTE networks. They proposed the use of a virtual BS called enhanced Nobe-B (eNB). Such nodes have a middle layer called hypervisor. This hypervisor is responsible for distributing resources among various virtual instances implemented on the higher layer. Such resource scheduling depends on different metrics including conditions for the user channel, the traffic loads, the priorities, the QoS requirements and the contract information for each virtual operator. They also proposed to divide the available spectrum into small and similar units called Physical Resource Blocks (PRBs), which will be allocated to the virtual operators. They implemented two algorithms for their scheme. The first one is a static algorithm, in which the spectrum is divided and assigned for each virtual operator which can keep using it for the whole time. The second algorithm is a dynamic version in which the resource allocation has to be done during runtime. Therefore this allocation and the amount of resources can vary over time based on the load of the operator's traffic.

The authors in (Luo et al. 2012) presented the Software Defined Wireless Networks (SDWNs) architecture. This work is considered as one of the earliest works proposing to use SDN for wireless communication. Using SDN was extended to cover Wireless Sensor Networks (WSNs) (Dutta et al. 2010). SD-WSN provides an SDN based framework to handle WSNs common management problems such as manual reconfiguration of WSN (Luo et al. 2012). In (Li et al. 2012) the authors claim that SDN can make cellular networks much simpler and easier to manage.

The first integration between SDN and CRN was presented in (Dutta et al. 2010). Neither virtualization was used nor resource allocation algorithm was proposed in (Dutta et al. 2010).

III. PROPOSED FRAMEWORK

We now discuss the proposed framework. We consider a network with one BS and n physical radio nodes (PNs) with varying sets of resources. For simplicity, we assume that these resources include a number of RIs at each PN and a set of orthogonal channels[1] available for specific periods of time based on the PU's activity along with constraints on the power levels that can be used for transmission in order to achieve several non-conflicting concurrent transmissions. Additional resources such as coding schemes can be easily incorporated into our framework. The existence of multiple channels and multiple RIs at each PN requires some access coordination which is achieved using multiple transreceivers per node (Sachs and Baucke 2008).

Each one of the PNs hosts a set of virtual nodes (VNs). VNs residing in different PNs may need to communicate with each other. To facilitate such communications, VNs request resources from their hosting PNs. The merits of our scheme are most evident when we are dealing with a heavily loaded network, which is characterized by two ratios. The first one is the ratio of the number of VNs residing at any PN to the number of available RIs at the same PN (VNs - RIs). This ratio can be smaller or equal to one, where each VN will be assigned one or more RIs, or it can be larger than one, where a number of VNs will have to take turns using the same RI, which can be achieved using any time sharing policy such as Time Division Multiple Access (TDMA). The second ratio is the ratio between the number of VNs residing in any PN and the number of available channels at the same PN (VNs - CHs). Again, this ratio can be smaller than or equal to one, where each VN will be assigned one or more channels. It can be larger than one, where a number of VNs will have to take turns using the same channel. This can be done using Frequency Division Multiple Access (FDMA) procedure or TDMA procedure. We focus our attention on the more interesting and challenging scenario in which both ratios are greater than one.

Different VNs residing on different PNs form virtual networks (VNets). See Fig. 1. VNs of the same VNet communicate with each other using the physical resources of the PNs. The goal of our proposed framework is to coordinate the access to these resources with minimal control overhead. Note that the discussion in this work is meant to be as general as possible without enforcing a specific meaning of VNets. Nonetheless, to give a concrete example, consider a scenario in which PN j_1 has a stream of packets to be broadcasted to a set of PNs, $j_2, \ldots, j_n$. Then, for each PN j_i, where $i = 2, \ldots, n$, j_1 creates a VNet consisting of two VNs: one residing in j_1 and one residing in j_i.

To achieve our goal of resource sharing with minimal control overhead, we propose a two-tier management scheme where the resources of the entire network is managed by a middle layer at the BS called the Global Hypervisor (GH). The GH allocates resources to the PNs where they will be managed by another middle layer at the PN called the Local Hypervisor (LH). LHs allocate the available resources to the different VNs running on them. Obviously, the resources are allocated based on their availability as well as the requests made by the VNs. A critical aspect to the success of this approach is the ability to avoid both the contention between SUs and any potential conflict with PUs. To address the former issue of coordinating SUs' access to the resources, the GH must assign the resources to the LHs in a way that allows each LH to make local decisions on how to utilize the resources assigned to it without interfering with other LHs. GH can use any fairness scheme to distribute the available resources among the LHs. As for the latter issue of avoiding interference with PUs' communication sessions, cooperative sensing is exploited in which each SU sends periodic sensing reports to the BS.

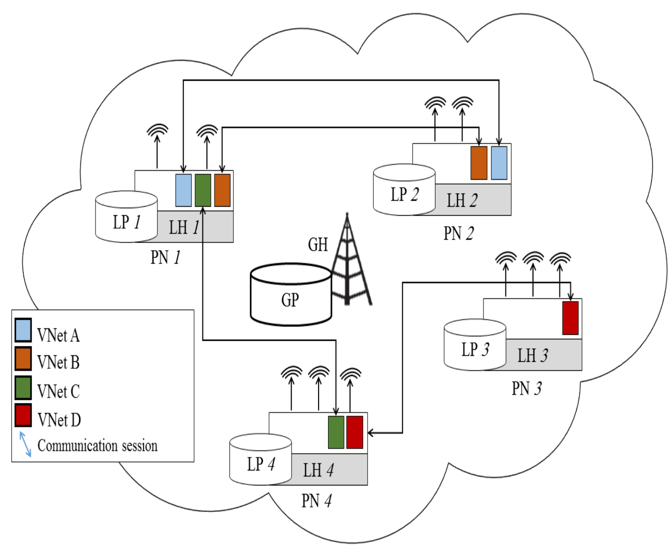

Fig. 1. Virtual network architecture

The following subsections discuss the steps of the proposed resource allocation framework as depicted in Fig. 2. The discussions therein pertain to specific resources: the RIs and the available channels; similar techniques can be applied to other resources.

A. Tier 1: Global Hypervisor (GH)

As mentioned before, the objective of the GH is to globally manage the resources of the entire network while the local management of the resources is left to LHs. In this subsection, we discuss the details of how this can be achieved.

[1] The unrealistic assumption of orthogonality between channels is made here for simplicity. It can be relaxed by introducing guard bands (Bany Salameh 2010).

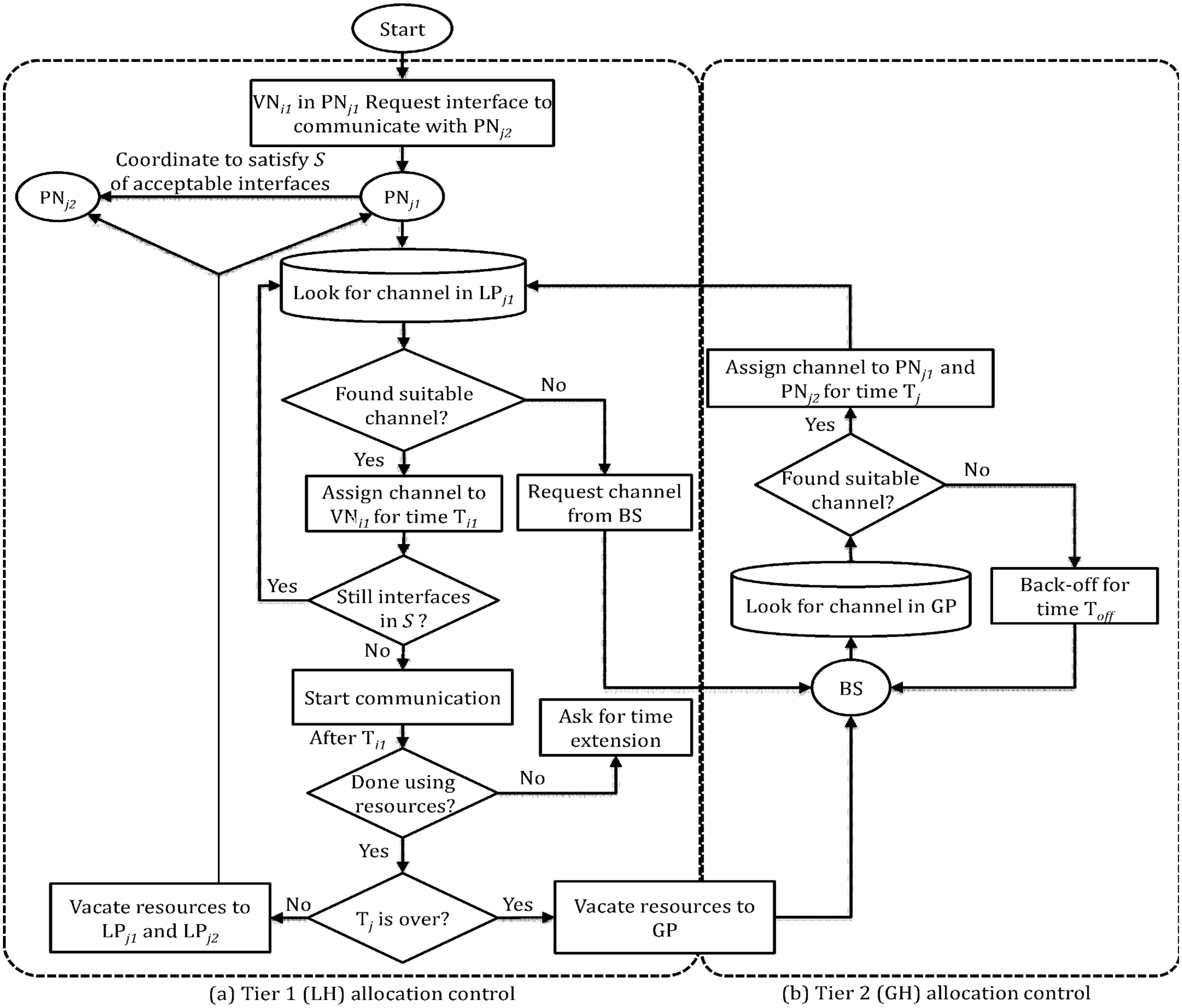

Fig. 2. Allocation flow control

When the GH receives a request from the LH of some PN $_j$ (LH$_j$) for a certain number of channels to be used for a certain period of time (requested time), it will check whether enough channels are available at the Global Pool (GP). If not, then the GH will wait for a specific period of time to determine if some channels can be vacated from other nodes in the network to satisfy the request. When the waiting period is expired, the request is dropped.

Now, if there are enough channels to satisfy the request, the GH will assign them to LH$_j$. For each channel c assigned to LH$_j$, the GH sets an upper limit on the transmission power that can be used by j. The transmission power is selected such that for each transmission from PN s (to some PN t) that belongs to the set Jc of concurrent transmissions on channel c, the following SINR equation is satisfied (Al-Ayyoub and Gupta 2010, Khreishah et al. 2009):

$$\frac{\frac{p_s}{d_{s,t}^{\alpha}}}{\mathrm{N}+\sum_{j\in J_c}\frac{P_j}{d_{j,t}^{\alpha}}}\geq\beta,$$

where P_s is transmission power from s, N is the white noise, $d_{s,t}$ is the distance between s and t, α is the path loss exponent usually assumed to be greater than 2 and β is the SINR threshold that depends on the desired data rate, the modulation scheme, etc. The GH resource allocation control is depicted in the right-hand side of Fig. 2.

Note that the GH assigns the upper limits on the power levels such that even if each transmitter uses the maximum allowed power, Equation 1 will still be satisfied at each receiver of all concurrent transmissions. This means that the GH need not be aware of the details of every communication session taking place in its region as long as each node is restricting itself to the assigned power limits. Nonetheless, if the GH is informed of the current transmissions, it will be able to better utilize the channels. This can be achieved by piggybacking such information into the control messages sent from the LHs to the GH such as sensing information, and requests for more resources.

Channels are vacated due to many reasons such as a PU starts to use the licensed channels, the requested time expires, communication session is over before the end of the requested time, etc. In some cases, the LHs might ask for an extension of the requested time, such requests are granted provided that no starvation or interference is caused.

B. Tier 2: Local Hypervisor (LH)

A LH at a certain PN is responsible for allocating the available resources to the VNs running on the PN. In accordance with the common terminology in the literature, we say that each LH has a local pool (LP) of resources obtained from the GH's global pool (GP) of resources. Obviously, the resources are allocated based on their availability as well as the requests made by the VNs.

When a VN *i1* (residing in PN *j1*) wants to communicate with another VN *i2* (residing in PN *j2*) in the same VNet,[2] both *i1* and *i2* have to request the resources necessary to complete their communication sessions from their respective LHs. For simplicity, we assume that these resources include the number of RIs from *j1*, the same number of RIs from *j2*, the number of channels that are available at both *j1* and *j2* and the ability to transmit at an appropriate power level at both *j1* and *j2*. Additional resources such as coding schemes can be incorporated easily into our framework. These resources are requested for a specific period of time. The LHs have a specific time period during which they must satisfy the request or drop it. Note that the request can be single-minded (where the request must be satisfied completely or rejected) or best-effort (where the request is made for specific amounts of each resources, but it is acceptable to be assigned a certain fraction of the original request). Either way, there will always be a minimum set of resources acceptable for any request.

To satisfy the minimum requirements of resources for a given request, the LH at *j1* must coordinate with the LH at *j2*. The two LHs should be willing to assign enough RIs to each VN and they should agree on a set of channels to be used for communication at acceptable power levels. These channels must be available at the local pool of each LH. If this is not the case, the channels (along with the acceptable power level) must be requested from the GH by the LH of the sender, *j1*. If there are enough channels available at the GH, then they will be assigned to the LHs. Otherwise, the GH will wait for a specific time period to determine if some channels can be vacated to satisfy the request. When the waiting period is expired, the request will be dropped. The LH resource allocation control is depicted in the left hand side of Fig. 2.

[2] Instead of assuming that one VN sends packets and the other VN receives them, we assume here the more interesting case of two-way communication.

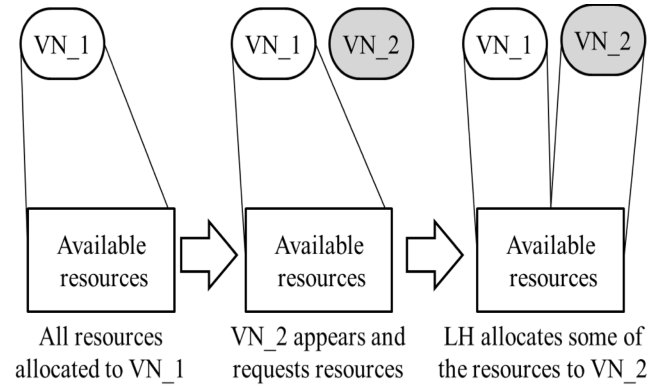

Fig. 3. Scale down resources

C. Dynamic Resource Allocation

An important aspect of virtualization is the ability to dynamically allocate the available resources to competing entities. In our framework, this means that when a VN is trying to establish a communication session on a PN with a small total of requested resources, then this VN might get all the resources it requests. As more VNs emerge and request resources, the amount of resources available to each VN decreases. This scenario of scaling down the resources is depicted in Fig. 3. On the other hand, if some communication sessions are completed and their allocated resources are vacated, the amount of resources available for each VN increases. This scenario of scaling up the resources is depicted in Fig. 4.

It should be noted that the procedures of scaling up and down the resources are not as straightforward as they seem due to the potential interference with other concurrent transmissions (e.g., if a channel *c* is currently being used by *i1*, it cannot be simply used by another VN, *i2*, if *i2* requires a transmission power level that is high enough to interfere with other concurrent transmissions over *c*). Note that based on our previous discussion, a decision on how to handle the newly available resources at the LH should be investigated. The first option is to perform a scale up procedure and allow other VNs at the same PN to utilize these resources. The other option is to vacate the resources and return them to the global pool. This decision is directly related to the fairness policy. A thorough exploration of this issue is the subject of future research.

IV. PERFORMANCE EVALUATION

We evaluate the performance of our proposed SD-CRN framework using simulation. The simulation results presented below are based on the average of ten independent simulation runs, each lasting for 2000 seconds. The experiments setups use a single cell with a varying number of PNs scattered within a region of 500 x 500 meters, a varying number of channels, and different problem scale ratios ((VNs - RIs) and (VNs - CHs)).

Three main simulation scenarios are used. The first scenario is concerned with the effect of varying the number of VNs residing at each PN while fixing the number of PNs, channels and RIs per PN. The considered values are 1, 3, 5 and 7. The case in which each PN has a single VN is equivalent to the non-virtualized framework. This scenario compares the performance of the virtualized and non-virtualized frameworks and shows how increasing the number of VNs per PN affects the performance of SD-CRN. The second and third scenarios are carried out to evaluate the effect of considering different values for the (VNs - RIs) ratio (in scenario 2), as well as different values for the (VNs - CHs) ratio (in scenario 3). The last two scenarios are done by interchangeably fixing one ratio and use different values for the second ratio. Different values for both ratios were used (less than, equal to or greater than 1). We assume that each time slot in all simulation runs represents 10 seconds.

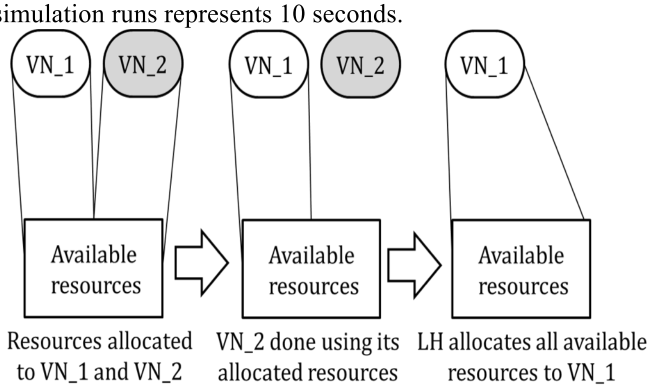

Fig. 4. Scale up resources

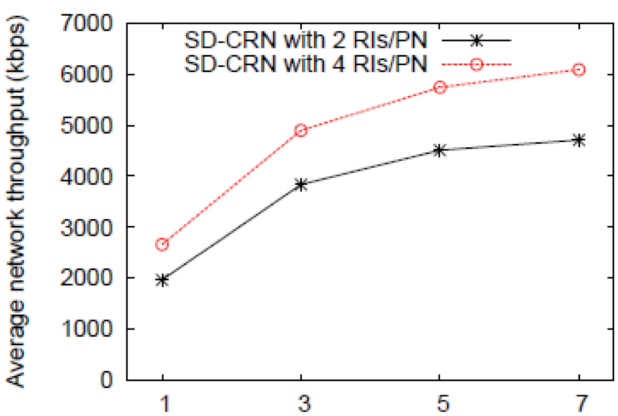

Fig. 5. Average network throughput of SD-CRN

Fig. 5 shows how SD-CRN framework improves the average network throughput. Intuitively, allowing multiple VNs to coexist and share the available resources on a single PN as well as reducing the need to communicate with the BS per request saves the time required to communicate with the BS and use that time for transmitting packets between the source and the destination in the different PNs. This increases the network throughput when using the virtualized framework for up to 300% (when using 7 VNs per PN). On the other hand, the results show that increasing the number of RIs for each PN results in a significant improvement on the network throughput for SD-CRN framework since, in SD-CRN setting, increasing the number of RIs means that the LHs try to retrieve more channels from the BS for each request (to be used for future local requests) as well as allowing multiple VNs at the same PN to share these acquired resources.

Fig. 6 shows the improvement achieved using SD-CRN framework on the network overhead. In most traditional frameworks, every request must be forwarded to the centralized BS to be replied with suitable resources or blocked if the minimum requested resources are not available. On the other hand, in SD-CRN, irrespective of the number of VNs residing at each PN, the results show that the network overhead is almost fixed after a specific period of time. Since, each PN keeps using the channels available on its own LP, based on the fairness policy discussed before. This reduces the control packets forwarded to the BS.

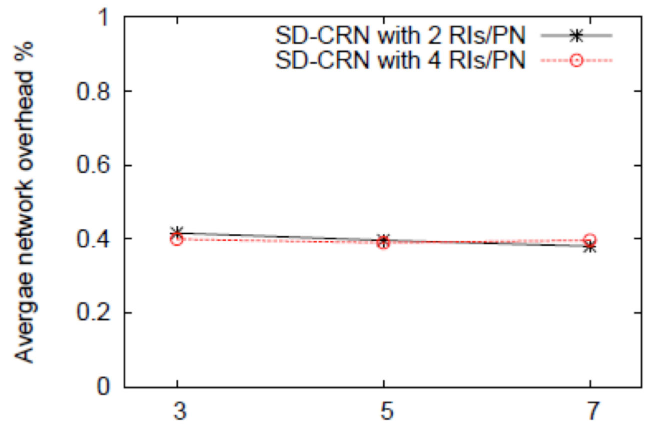

Fig. 6. The network overhead computed by taking the ratio between the number of control messages sent by SD-CRN and the number of control messages sent by a non-virtualized framework.

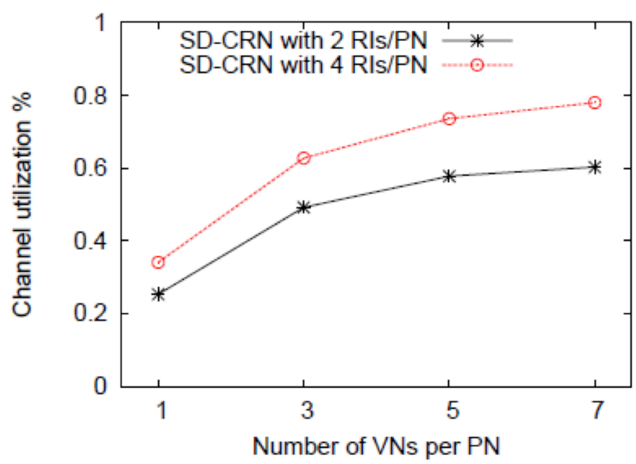

Fig. 7. Channel utilization between SD-CRN and non-virtualized.

From the results shown in Fig. 7, channel utilization is increased from about 34% when using 1 VN per PN to about 78% when using 7 VNs per PN with the same number of available RIs per PN. Intuitively, allowing more instances of VNs to instantiate their own communication sessions within a single PN plays a significant role in improving the channel utilization. This is because, in SD-CRN, concurrent transmissions can be achieved simultaneously, which means maximizing the benefits gained from the available resources in hand. On the other hand, more traffic is allowed for a specific period of time.

Now we discuss the second scenario, in which the network performance is measured in terms of (VNs - RIs) ratio. In this scenario, we fix (VNs - CHs) to be (2 - 1). This allows us to determine the effect of the network performance caused by the availability of RIs per PN.

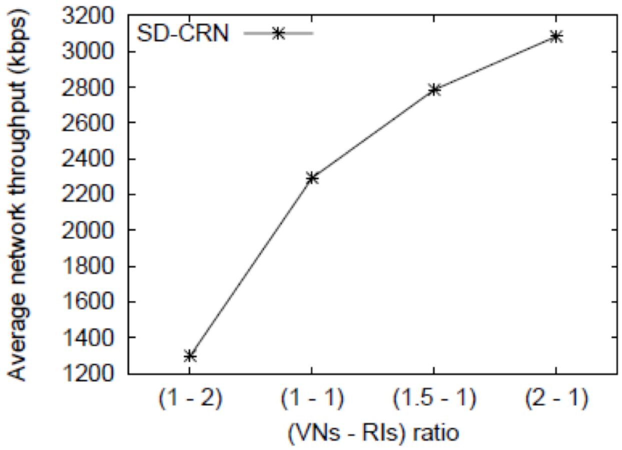

Fig. 8. Average network throughput with different (VNs - RIs) values.

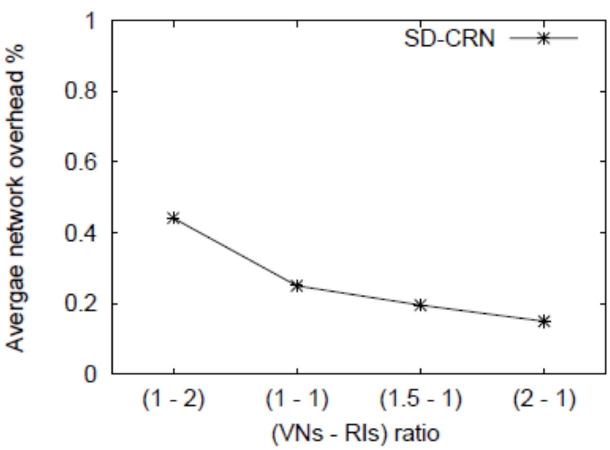

Fig. 9. Average network overhead with different (VNs - RIs) values.

Fig. 8 shows that the greater the ratio is being used the greater the improvement of the average network throughput. Obviously, having more VNs per PN allows more traffic which in turn results in maximizing the network throughput for about up to 230% rising from (1 - 1) up to (2 - 1) ratio.

One of the most important aspects of the proposed SD-CRN framework is the reduction in network overhead, which is presented in Fig. 9. Again, the more the demand on the available resources (channels and RIs) the more the amount of the available resources on the LP for each PN which results in more options for future requests that can be satisfied using these resources with minimum number of packets needed to communicate with the GH. So, in this scenario allowing more VNs to coexist within a single PN means more demand on resources which in turn increases the availability of resources on the LP.

Fig. 10 shows that the channel utilization is decreased using greater ratios with (1 - 2) ratio allowing maximum utilization. This comes from the fact that using a greater number of RIs decreases the number of blocked requests caused by the unavailability of RIs since, in SD-CRN setting, the request might be blocked either because the unavailability of RIs or the unavailability of channels. This allows more traffic to be achieved within a specific period of time.

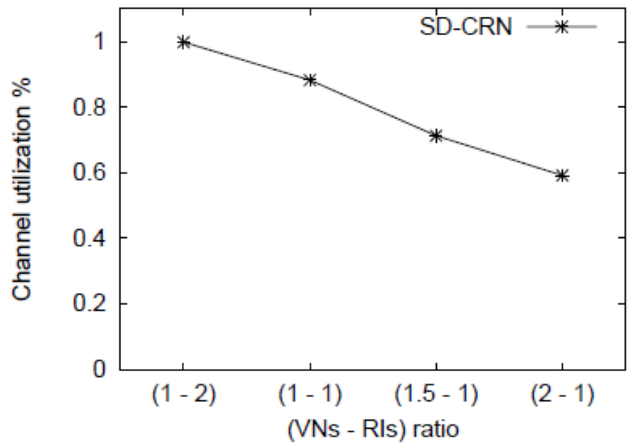

Fig. 10. Channel utilization using different (VNs - RIs) values.

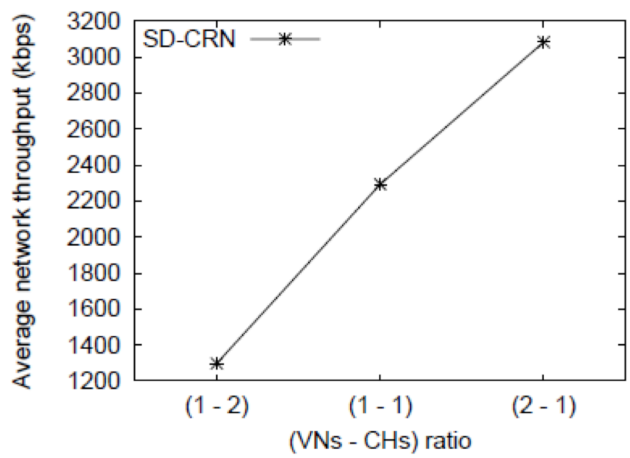

Fig. 11. Average network throughput with different (VNs - CHs) values.

Finally, in the third scenario, we study the network performance with respect to the (VNs - CHs) ratio. In the following discussion, we fix the (VNs - RIs) ratio to be (1 - 1), to ignore the effect of the network performance caused by the unavailability of RIs. This allows us to determine effect caused only by the unavailability of channel for each VN.

Fig. 11 shows that the average network throughput is increased while increasing the number of available channels for each VN. This is a result of the number of blocked requests when using small number of channels, since they are both under same traffic load. It is obvious that having more resources leads to a higher throughput; however, this means that the channel utilization will be affected under such circumstances, because we need to get the most benefit of the available resources for a specific period of time. Again, having more resources means more chances for LHs to have more candidates on its own LP to select from, leading to a lower overhead.

Fig. 12 shows that the network overhead is decreased while increasing the number of available channels for each VN residing on each PN, from about 45% when using (1 - 2) ratio to about a 15% when using (2 - 1) ratio.

Fig. 13 shows that using a ratio bigger than 1 increases the channel utilization to be closer to the peak amount that the available resources can handle, by trying to keep the channels as busy as possible. The channel utilization was decreased significantly using smaller ratios to reach less than 60% when using (2 - 1) ratio.

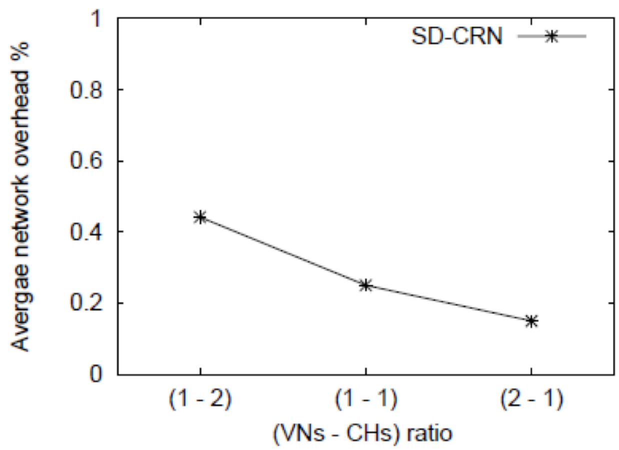

Fig. 12. Average network overhead with different (VNs - CHs) values.

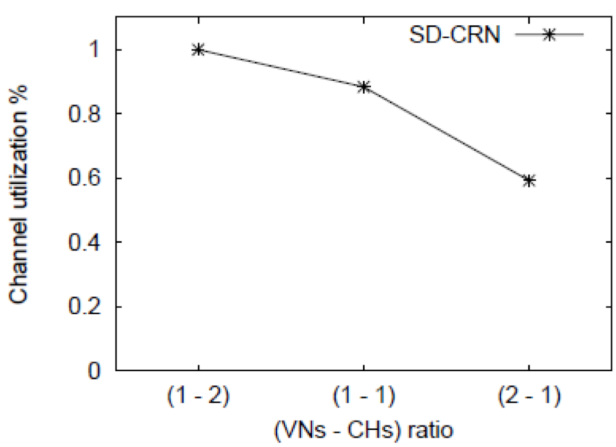

Fig. 13. Channel utilization using different (VNs - CHs) values.

V. Conclusion and Future Work

In this paper, we proposed SD-CRN, a virtualization based dynamic resources allocation framework for CRNs. The framework uses the concept of multilayer hypervisors for efficient resources allocation. It also introduces a semi-decentralized control scheme that allows the CRN BS to delegate some of the management responsibilities to the network users. The CR resource virtualization principle allows dynamic, infrastructure free and efficient resource allocation to the CRN users. The main objectives of the framework are to reduce the CRN users' reliance on the CRN BS and to improve the network performance by reducing the control overhead while improving the network throughput and the channel utilization. The simulation results showed that significant performance improvements are obtained with the use of SD-CRN framework, since the proposed SDCRN framework was able to justify the network overhead over time irrespectively to the other parameters used, which means improving the overall network performance. By looking into the results presented in the previous section, we noticed that SD-CRN introduced significant improvements to the network performance which can be summarized as follows:

- The network BS management overhead was reduced by decreasing the amount of control packets transferred between the network PNs and the BS, which came as a result of delegating some of the management overhead to the network PNs.
- The network throughput improved significantly, which came as a result of allowing multiple VNs on the same PN to concurrently communicate with other VNs residing on other PNs, each of which belonging to a different VNet.
- The network channel utilization improved by allowing multiple VNs to start their own communication sessions concurrently.

The previous attempts to integrate the concept of virtualization into CRNs are not mature enough, which makes it a very interesting field with several challenges. For example, we are looking to apply some kind of scheduling scheme between different VNs within the same PN using TDMA and FDMA. Moreover, a thorough exploration of the fairness policy when performing the resource scaling up and down procedures is a subject of future research. Finally, we are planning to apply more practical and efficient power control mechanism for both the GH and the LH.

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