A Framework for Interference Control in Software-Defined Mobile Radio Networks

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***Abstract*—To cope up with the booming of data traffic and to accommodate new and emerging technologies such as machine-type communications, the 5th Generation (5G) of mobile networks must be empowered with efficient resource allocation schemes that benefit from the adoption of the Software-Defined networking (SDN) paradigm. In radio communications, allocation of resources is tightly connected with interference. In this paper, we revisit the way wireless interference is managed and avoided relying on the SDN paradigm for controlling the network. The SDN approach is exploited to expose the lower layers of the stack (e.g., Physical and Medium Access Control) to the controller and its applications by making system parameters available, such that it is possible to dynamically configure the network in a logically centralized fashion, by means of specifically designed algorithms. The contribution of this work is threefold. First, we show how to adapt the SDN paradigm to mobile networks. Second, we propose the interference graph as an abstraction that can be used to control interference. Last, we formulate a throughput optimization tool that uses the proposed interference graph as an input.**

***Index Terms*—Software–Defined Networking, 5G, mobile network, abstractions, interference graph.**

I. Introduction

With the rapid increase of services and user data traffic demand transported over the mobile network, node deployments become more dense resulting in significantly higher levels of wireless interference. This is the case of communications taking place in the 2.4 GHz ISM band as well as for the 4G UMTS Long Term Evolution (LTE) and its advanced development LTE-A, which uses a frequency Reuse 1 approach. This problem will be further exacerbated with small cells deployment and future 5G communication systems that will make the network even denser. Interference is the number one enemy of radio communications limiting coverage, capacity and more in general efficiency. Current network control and management tools lack scalability, flexibility and reconfiguration capabilities that modern telecommunication systems ought to have.

Software-Defined Networking (SDN) [1] is one of the emerging new network architecture paradigms promising innovation in terms of network programmability by allowing network control and management whereby high level abstractions. This is achieved by separating the control (which decides where traffic is addressed and how) and data planes (simply forwarding flows of data packets) with well-defined programmable interfaces in order to provide i) a centralized global view of the underlying network and ii) an easier way to configure and manage the network whereby the abstractions. Future mobile communications that are moving toward 5G will require unprecedented flexibility, scalability and reconfiguration capability of different network segments. One severe limiting factor to the efficiency of radio communications is interference. This problem was studied for decades and many different solutions at both physical layer (PHY) and medium access control (MAC) layer have emerged with time but so far none of them managed interference satisfactorily.

In this paper, we first deem to extend the concepts of SDN to mobile radio networks in such a way to lend to generalization of the SDN approach. Doing such an endeavor is currently under study in several research studies [1], [2] despite the SDN concepts cannot be directly applied in the wireless domain. The contribution of this work is threefold. First, we focus on 4G LTE cellular networks and we show a possible way to map the concept of SDN to a 4G evolved Node B (eNB) looking the problem at the transmitter side (although it holds similar for the receiver). Second, starting from this mapping we identify a set of network related parameters that can be exposed to the upper layers in the form of abstractions. This set includes typical radio parameters such as transmitted power, code rate of the forward error correction (FEC) and 4G specific parameters such as modulation and coding scheme (MCS) and number of antenna elements in a multiple input multiple output (MIMO) antenna system. Based on that we develop an interference graph (IG) abstraction that can be used by the SDN controller to optimize network segments using several practical constraints. Therefore, tuning parameters in the IG will be reflected by a different configuration of interference. Last, we present a formulation that can be used in a control loop to optimize the behavior of the network as a whole in a portion of space, according to the information provided by the IG.

The reminder of the paper is organized as follows. Section II describes the related works in the area. In Section III, the system design and architecture is presented. The problem formulation and system interference modeling is discussed in Section IV and V respectively. The resource allocation and optimization is explained in Section VI. Finally, conclusions are drawn in Section VII.

II. RELATED WORK

In this section, we discuss the most notable research works that are closely related to ours. OpenFlow wireless (also known as OpenRoads) [2] prescribes that users can move freely between any wireless infrastructure while providing billing functions to infrastructure owners, which could motivate CAPEX. It uses FlowVisor [3] for network slicing and to handoff the control of different flows to different controllers. OpenRadio [4] is a design that gives modular and declarative programming interfaces by separating the wireless protocols into two planes, processing and decision. This provides a way to build a network abstraction to find a trade-off between performance and flexibility.

The sub-optimality of distributed control system in cellular networks (e.g., 4G LTE) is the main motivation behind SoftRAN [5]. The target of SoftRAN is to design a centralized control-plane for radio access networks (RANs) to address the issues related to radio resource allocation, interference reduction, handover and load balancing to yield system performance improvement. The design goals are achieved by aggregating base stations in a wider virtual base station and a centralized control system. In contrast to OpenRadio and SoftRAN, in which the ideas concentrate around the radio part of the cellular system, SoftCell [6] addresses the issues of inflexible and expensive equipment and complex control plane functions in cellular core networks using commodity switches and servers. Simulations and realistic LTE workload emulations on SoftCell show improved scalability and flexibility in cellular core networks.

The work in [7] proposes the concept of a virtual cell (V-cell) with an architecture aiming to overcome the technical limitations of Layer one and Layer two in conventional wireless networks. V-cell abstracts all the resources provided by a pool of base stations into a single large resource space to a centralized control-plane in the SDN RAN controller. The resource space which is also known as $ResoucePool$ is a n-$dimensional$ (i.e., time, frequency, space, power, etc.) matrix of LTE resource blocks (RBs).

Several ways of representing interference are available in the literature. In [8] a detailed survey of interference models in wireless ad hoc networks is presented. Three major groups are identified as follows

- Statistical interference models: they assume the aggregate interference as the sum of individual interfering signals. The main drawback of this model is that closed-form expressions for the aggregate interference distribution exist only in specific network deployments.
- Models that describe the effect of interference: they are divided in two groups. Protocol Interference Models, based on the vulnerability area capture model of transmitter and receiver pairs. These models are simple and facilitate IG construction. Physical Interference Models, which consider transmitter receiver pair and computes the aggregate interference mainly using the threshold Signal-to-Interference-plus-Noise Ratio (SINR) (i.e., transmission will be successful $iff\ SINR \geq \beta$).
- Graph-based interference models, which exploit elements of Graph Theory to analyze interference between terminals and links.

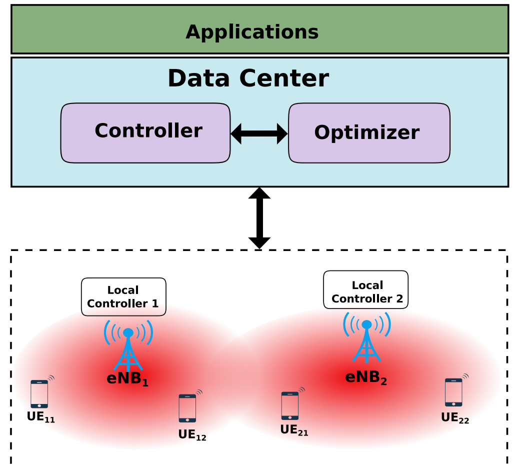

Fig. 1: Software–Defined Mobile Radio Access Network architecture [7]

III. SYSTEM DESIGN

The high-level system architecture for a Software-Defined wireless network that split the functionalities of control and data planes to leverage an efficient resource allocation scheme with reduced interference is presented in Figure 1. The actual network elements are at the moment 4G eNBs and heterogeneous radio access technologies (RATs) small cell base stations. The leaf nodes of this architecture are the user equipments (UEs). Both network nodes will be implicit assumed in the remainder of the paper and the system architecture will be used as basis for the discussion hereinafter.

A. System Architecture

The upper part of Figure 1 show the controller. This is the core element of the architecture responsible for some of the most important (re)configuration functionalities of the network. The controller interfaces to different applications that are involved in programming the abstractions exposed by the lower layers of the protocol stack with a goal of improving the performance and manageability of the (geographically) wide network. Relying on a global network view (i.e., radio resources from each base station), the controller facilitates optimization of resource scheduling. In addition, all decisions that allow latency constraint relaxation are taken by the controller and then passed to the underlying network (e.g., small cell devices). Other functions of the controller include managing the no-handover area between base stations, virtualization of the wireless network (i.e., coexistence of different RATs) and interference management.

The local controllers provide the local control plane of each base station as a result of separating the control plane from the underlying physical infrastructure. Each local controller

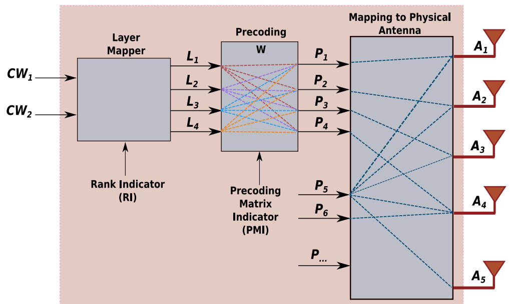

Fig. 2: The Switch Port Analogy for Wireless Networks.

could also be seen as the abstraction of the radio resources that are available for scheduling in each base station. The local controllers are responsible of taking short-time scale (sub-milliseconds) local decisions. Moreover, the feedback information collected from each UE is forwarded to the $Data\text{-}Center$, which aggregates distributed information in a centralized storage, through the local controllers.

The optimization subsystem collects information from the network (i.e., based on the global view) and performs optimization of multiple parameters for the active links in the underlying wide network targeting to minimize / maximize some predefined cost functions. For each resource allocation request from the UEs the optimization subsystem computes the optimal allocation of RB, MCS, transmitted power (P_{Tx}) and MIMO parameters.

B. *Revisiting SDN for cellular networks*

After the optimal selection of resources for a set of links, the following step consists of deciding how the information should be transmitted through the air–interface. In wired Local Area Network (LAN), switches have a set of input ports (I_i) that are mapped into outputs (O_i) where the mapping is done based on specific rules contained in a *forwarding table*. In mobile network input code-words (CWs) are mapped to physical antenna ports (see Fig. 2) where the mapping, which consists of selecting modulation and coding schemes, transmission power, etc. is driven by the actual channel conditions.

Depending on the channel feedback information received from the UEs, the controller have to decide whether relying on diversity in the transmission or use spatial multiplexing and beam-forming. As shown in Figure 2, the mapper block maps the streams in layers depending on the rank of channel impulse response. In other words, the number of independent spatial layers that contains serial-to-parallel blocks to facilitate the mapping accordingly. The precoder (W), which is determined by the Rank Indicator and the number of antenna ports, is a codebook defined by 3GPP specifications. This is a complex weight used for each layer to match the transmission to the propagation conditions of the channel, which results in mapping each layer to one or more logical antenna ports. The mapping of antenna ports to the physical antennas varies from base station to base station and from vendor to vendor [9]. This mapping is identified by the UE automatically by demodulating the Reference Signal transported over a RB depending on the number of antenna ports used for the transmission. Combining all the components, equation (1) shows a more formal representation of the output vector (Y) at the physical antennas as a function of the input vector X of code-words and matrix ($\mathbf{H}$) that accounts for the mapping described above.

$$\overline{Y} = \mathbf{H} \cdot \overline{X} \ , \tag{1}$$

where the size of $\overline{X}$ is a vector of size equal to the number of CWs and $\overline{Y}$ is a vector of size equal to the number of physical antennas. Thus, the selection of $\mathbf{H}$ is done by the centralized controller based on the channel feedback information of the UEs. The output of each physical antenna port can be represented by a tuple of parameters representing an abstraction of the resources assigned to a stream of packets.

IV. Problem Formulation

In this section, we present the formulation of the interference control framework that is the key contribution of this work. The flow chart in Figure 3 shows the functional components that have to be part of the central SDN controller shown in Figure 1. Referring to cellular LTE/LTE-A networks, a resource is a multi-dimensional element that can be characterized by a tuple of parameters as follows: $<time$, $frequency$, $space$, $transmit\text{-}power$, $modulation$, $coding$, $antenna\text{-}port$, $beam\text{-}pattern>$. Each of these parameters have different impact on PHY and MAC layers functions. More in specific, for this work we envision the situation that rises as soon as small cells base station will be deployed, although the description of the framework is general enough to be suitable in many types of contexts.

Using the Software-defined paradigm for wireless networks, we aim to design a suitable abstraction to be exposed to the upper layers whereby optimizing globally the underlying network and to formulate an efficient resources allocation optimization that relies on controlling the aggregate interference. Accordingly, two tightly connected representation of the network are the bonds between interference and network connectivity. Namely, they are the IG and the conflict graph (CG) that descends directly from the IG.

The IG models the interference among communication links. The goal here is to establish an autonomous framework to reduce/avoid interference. Based on the IG the conflict graph gives an insightful representation of the way the interference of each transmission links affects the others. In essence, to each interfering link is assigned a weight that corresponds to the amount of interference generated by the interferer on other receivers. The optimizer block shown in Figure 3 makes the attempt to minimize these weights globally targeting a lower level of aggregate interference within a certain spatial region. The information that is transmitted to a recipient is then fed to a physical antenna port. Therefore, each information at the output of a port (i.e., the concept of port for LTE networks revisited in light of SDN is shown in Figure 2) is represented by the tuple of parameters explained above. The loop in Figure 3 represents the continuous monitoring of the network through

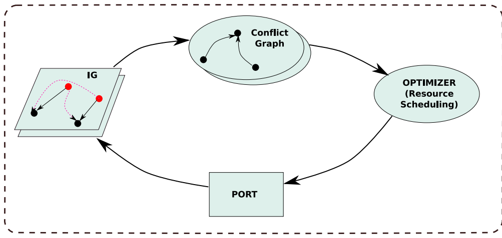

Fig. 3: Functional view of interference control framework running inside the central SDN controller.

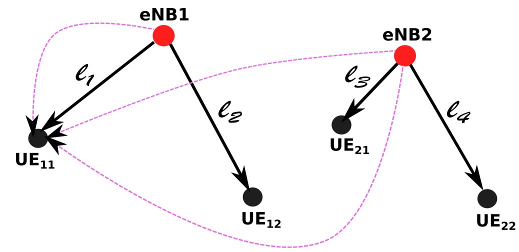

Fig. 4: IG (purple dashed lines) built on top of the connectivity graph between transmitter-receiver pairs (black solid lines).

which feedback information is collected from the UEs, sent to the ports and fed back to the IG block.

Based on Shannon's capacity equation as shown in (2), we can see the dependencies of the PHY layer parameters on the capacity. Where B is the channel bandwidth and N_0 is the two-sided noise power spectral density.

$$C_i = B \log_2 \left(1 + \frac{P_i |X_i - X_{R(i)}|^{-\eta}}{N_0 B + \sum\limits_{k \neq i} P_k |X_k - X_{R(i)}|^{-\eta}} \right) , \quad (2)$$

where P_i is the transmitted power, which is the power for a transmitted symbol. For each symbol encoded with N bits the power of one symbol is obtained by $P_i = \sum_{i=1}^{N} P_i^{(\text{bit})}$, where P_i^{bit} is the transmitted power per bit. In order to determine the suitable modulation index (that in turn determines the value of N) for a certain transmission, the method could rely on using existing constraints on the desirable bit error probability (P_{e}) for a communication link. Upon fixing a desirable value of P_{e} it is possible to compute the average SINR, which is directly connected to the modulation scheme (e.g., QPSK or QAM) amongst other relevant network related conditions. In LTE/LTE-A a specific modulation and coding scheme (MCS) is selected depending on the received SINR that can be computed relying on the measurements fed back by the terminals. The antenna port number is another optional design parameter whose setting is automatically selected by the base station depending on feedback and channel state information.

V. Interference Modelling

This section presents the interference analysis starting from the construction of the connectivity graph from which IG and CG can be derived [8]. In order to account for the aggregate interference generated by different transmitters pairs on a reference transmission link, weighted CG is used as explained below [10].

A. Interference Graph

The IG is a graph characterized by the pair (V, E) that is used to represent the interference among different communication links (transmitter-receiver pairs) in the network. As mentioned in previous section, the network is intended here in a broader sense. Indeed a spatial region wherein different small cell base stations are deployed and communicating with UEs in range. In this scenario, V stands for the set of UEs in the wide network connected by edges that belong to the set E to represent the pairwise interference among neighboring communication links. The edge connecting two transmission links exists if the transmitter of one transmission link is within the interference range of a receiver that is part of another transmission link. An example of such graph is represented as dashed–lines in Figure 4. The directed edges (dashed–lines) indicate which nodes are interfering with which terminals.

For building the IG, the central SDN controller shown in Figure 1 should collect information from all the communication links for a certain period of time (construction of a history). In addition, it is also possible to compute the IG using micro-probing, which is done by injecting traffic into the network to infer the occurrence of interference. Even though micro-probing is quite accurate, the overhead is very demanding in large scale networks.

B. Conflict Graph Construction

Considering a set of transmitter–receiver pairs $\{(X_i, X_{R(i)}) \colon i \in \mathbb{N}\}$, where X_i and $X_{R(i)}$ represent the location of the transmitting and receiving terminals respectively. Focusing on a downlink transmission, the connectivity graph can be constructed as a directed graph from the eNBs (X_i) to the UEs ($X_{R(i)}$), see Figure 4.

According to the Physical Interference Model discussed in [8], to have a successful reception at the receiver $X_{R(i)}$, SINR $\geq \beta$. The maximum allowed interference level $I_{i,max}$ at the receiver is given by (3).

$$I_{i,\text{max}} = \beta^{-1} P_i |X_i - X_{R(i)}|^{-\eta} - \sigma^2 , \quad (3)$$

where P_i represents the transmit power of the eNBs, σ^2 is the additive noise power and η is the path loss exponent. The maximum allowable interference contribution of the k-th interfering link $(X_k, X_{R(k)})$ on terminal $X_{R(i)}$ is with the fraction given by (4).

$$w_i^k = \frac{P_k |X_k - X_{R(i)}|^{-\eta}}{I_{i,\text{max}}} \quad (4)$$

$$\sum_{l_k}^{S_m} w_i^k \leq 1 \quad (5)$$

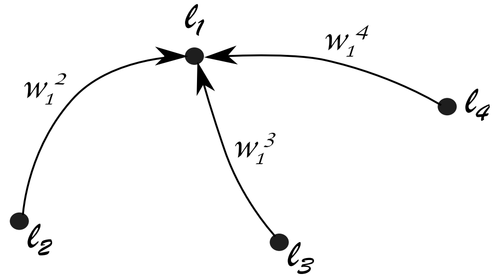

Fig. 5: Conflict Graph construction, which descends from the Interference Graph, gives a clear information concerning the strength of interference among links.

Let l_i as the communication link between transmitter-receiver pair $(X_i, X_{R(i)})$, being represented by a vertex in a weighted conflict graph. According to the model in [10], there is a weighted edge directed from vertex l_k to vertex l_i with a weight of w_i^k for $i, k \in \mathbb{N}$ and $i \neq k$. From the weighted conflict graph, which is shown in Figure 5, its possible to determine a set of communication links (i.e., $l_i \in S_m$) that could be active at the same time considering the expression in (5) is satisfied. Hence, the links $l_i \in S_m$ can be scheduled at the same time-slot, i.e., the aggregate interference caused by those links is below the allowed maximum interference level $I_{i,\max}$. Thus, the lower the values of each weight, w_i^k, on every edge results in more number of links included in S_m.

VI. Resource Allocation and Optimization

After constructing the conflict graph, the following step is to come up with a model that will lower the values of the weights w_i^k of the conflict graph. In order to account this, an efficient resource-scheduling/power-allocation technique needs to be adapted. The following section describes the important parameters that have a direct/indirect effect on the interference or system performance. Considering a base station (either macro or small cell) having L transmission links allocated we can define a set of tunable parameters which directly affect the conflict graph. The tunable parameters include: i) transmission links (UE, eNB) pairs $\mathcal{L} = \{1, 2, .., l, .., L\}$; ii) RBs (frequency, time, space) $\mathcal{R} = \{1, 2, ..., r, .., R\}$ and iii) MCSs $\mathcal{M} = \{1, 2, ..., m, ..., M\}$.

The objective here is to reduce the aggregate interference on a certain transmission link l_i, i.e., targeted to reduce the weight of the edges as in (4) , or to maximize the SINR at the receiver. Since the weights on the edges and the interference created by the interfering links are directly proportional, equivalently we can minimize the weights by optimizing the power allocation on each link [11]. The resource allocation problem that results in a reduced weights of the edges of a conflict graph can be formulated as an integer linear problem. Consequently, the objective function of the optimization problem is given as (6a) considering each link l_i corresponds to a certain down-link transmission with *(transmitter, receiver)* pair as shown in Figure 5 (i.e., solid black circles).

$$\min_{\varphi_{i,k,r,m}} \sum_{i=1}^{L} \sum_{\substack{k=1 \\ k\neq i}}^{L} \sum_{r=1}^{R} \sum_{m=1}^{M} w_{i,r,m}^{k} \cdot \varphi_{i,k,r,m} \tag{6a}$$

s. t.

$$\sum_{\substack{k=1 \\ k\neq i}}^{L} \sum_{m=1}^{M} \varphi_{i,k,r,m} \leq 1 \qquad \forall i, r, \tag{6b}$$

$$\sum_{m=1}^{M} \rho_{i,k,m} \leq 1 \qquad \forall i, k, \tag{6c}$$

$$\varphi_{i,k,r,m} \leq \rho_{i,k,m} \qquad \forall i, k, r, m, \tag{6d}$$

$$\sum_{r=1}^{R} \sum_{m=1}^{M} TP_{i,k,r,m} \cdot \varphi_{i,k,r,m} \geq TP_{i,k}^{ref} \quad \forall i, k, \tag{6e}$$

$$\rho_{i,k,m} \in \{0, 1\} \qquad \forall i, k, m, \tag{6f}$$

$$\varphi_{i,k,r,m} \in \{0, 1\} \qquad \forall i, k, r, m, \tag{6g}$$

$$P_{\min} \leq P_i \leq P_{\max} \qquad \forall i, k. \tag{6h}$$

Equations (6b) to (6h) represent the constraint functions for the optimization problem expressed in (6a) where the expression for $w_{i,r,m}^k$ is given in equation (4). $\varphi_{i,r,m}$in (6g) is a decision binary variable, which is 1 if link l_i uses MCS m in RB r or 0 otherwise. Similarly, equation (6f) is also a binary variable that is equal to 1 if link l_i use MCS m or 0 otherwise. Considering each eNBs constraint (6b) makes sure that RB r is only assigned to a single link l_i (i.e., for links served by the same transmitting eNB; if the links are in different eNBs then the $space$ component of the RB $<time$, $frequency$, $space>$ makes sure that each RB is assigned to single link), and constraints (6c) and (6d) together guarantee that each link is allocated to at most one MCS. Constraint (6e) makes sure that each link achieves its throughput demands $TP_{i,k}^{req}$. Finally the last constraint (6h) sets the interval for the possible transmission power level.

The objective function in (6a) minimizes the weight $w_{i,r,m}^k$ by optimizing the allocation of RB, transmit power and MCS in the overall network. The matrix $\mathcal{W}$, which is a 2-$dimensional$ $L \times L$ matrix gives the overall weight assigned to the edges of the conflict graph. Each row in $\mathcal{W}$ represents the interference on every single link in the presence of L-1 simultaneous transmissions.

$$\mathcal{W} = \begin{pmatrix} w_1^1 & w_1^2 & w_1^3 & . & . & . & w_1^L \\ w_2^1 & w_2^2 & w_2^3 & . & . & . & w_2^L \\ w_3^1 & w_3^2 & w_3^3 & . & . & . & w_3^L \\ . & . & . & . & . & . & . \\ w_L^1 & w_L^2 & w_L^3 & . & . & . & w_L^L \end{pmatrix}$$

Where the self-interference term w_i^i= 0. Therefore, minimizing the values of $\mathcal{W}$ means solving the integer programming problem represented by the cost function (6a) considering the constraints.

VII. CONCLUSIONS

In this paper, a general software-defined based framework for mitigating interference in mobile radio networks is introduced. Using the global view of the network, a centralized interference analysis enables an optimized radio resource allocation. A set of mobile network system parameters ,$<time$, $frequency$, $space$, $transmit$-$power$, $modulation$, $coding$, $antenna$-$port>$, are abstracted to higher layers in order to improve the programmability of the network. Moreover, the concept of switch port for wireless network is presented to further improve the flexibility of choosing the right mapping in a centralized manner.

This is a preliminary investigation. As part of the future works, we are currently working on implementing a software-defined wireless framework using an open-source hardware/software development platform called OpenAirInterface (OAI), which simulates the LTE protocol stack. Furthermore, we will carry out the system evaluation by resorting to different experimental simulations.

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