Cognitive Wireless Networks: Your Network Just Became a Teenager

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***Abstract*— In this poster we discuss research challenges one needs to overcome to introduce intelligent methods to wireless communications. Recent research on cognitive radios has started to introduce machine learning and reasoning techniques to wireless networks. However, while these first steps with cognitive radios are certainly exciting, they have been very limited in scope, and collaborative aspects of network optimization have largely been ignored. As protection against the chaos that could ensue from the kindergarten of selfishly behaving cognitive radios, we propose a cognitive resource management framework. Allowing for the distribution of information gathering and decision making across the network we hope to boost the collective intelligence of the system from the level of a toddler towards that of a teenager.**

I. Introduction

During the last decades development of wireless communication systems has been an immensely succesful endeavour. We have witnessed an explosion especially in popularity of technologies utilizing the license-exempt ISM frequency bands. Both Wireless LANs and Bluetooth are now available in practically every larger mobile terminal.

The dark side of this success story is the overcrowdedness one is already witnessing in these popular ISM bands. In the technology-homogeneous case the standard medium access control procedures can relatively effectively be used to share the wireless medium amongst communicating nodes. However, this solution is not anymore sufficient when numerous different technologies compete from the same spectrum. This is already a severe problem for new technologies especially in the 2.4 GHz ISM band. It is also arguable that more intelligent ("cognitive" and self-learning) methods could lead to better MAC utilization.

In addition to "traditional" interoperability solutions, such as the ones developed to mitigate WLAN-Bluetooth interference, more radical approaches have also been suggested. In particular spectrum agility techniques originally developed to reclaim momentarily unused parts of the strictly regulated radio spectrum can be exploited in the ISM bands as well. Key idea in these approaches is to reconfigure communicating radios with very rapid response times to use frequencies that are at the moment not used by their primary users.

Most interesting of these proposals is perhaps the suggestion of using adaptive machine learning techniques. These "cognitive radio" solutions were originally suggested for enabling dynamic spectrum management in licensed frequency bands to regain some of the unused spectrum but are suitable for solving the co-existance problems introduced above [1], [2]. In a sense we can view cognitive radios as extreme spectrum agile radios that in the ISM band case "borrow" spectrum from other users sharing the band, instead of a primary user authorized by some governing body.

Our major concerns with respect to the methods proposed so far are twofold:

1) It is very difficult to guarantee that heterogeneous population of cognitive radios that attempt to optimize their own spectrum usage can achieve even satisfactory global use of wireless resources. Collaboration in communication systems on single layer, network or link, has been studied in detail especially in game theory formalism (see, for example, [3], [4]). However, overall system analysis considering cross-layer aspects remains to be done.
2) Straightforward optimization of link and physical layer performance can lead to vast amounts of wasted capacity if no higher layer protocol or entity is able to benefit from it. We argue that "cognitive" techniques also offer an alternative to traditional cross-layer optimization which has proven to be more problematic than the initial optimistic works indicated [5].

Therefore, we propose extending the scope of the cognitive radio research towards more holistic approach. We introduce a framework for *cognitive resource manager* (CRM) enabling autonomic optimization of the communication stack as a whole, instead of focussing solely on the spectrum problem and thus going well beyond simplistic RRMs (Radio Resource Managers) and medium access control techniques. We further discuss the exchange of network information between the CRMs as a method to avoid harmful interactions arising from local optimization methods leading into globally unsatisfactory solutions. Communication between CRM instances could finally be used to federate individual cognitive radios to become *cognitive wireless networks* [6], [7]. This way the CRM would offer a systematic approach as a framework for *distributed* cross-layer optimization.

II. The CRM Architecture

In this section we discuss about the functions of the Cognitive Resource Manager (CRM) with more details. Its conceptual architecture is shown in figure 2. We see the

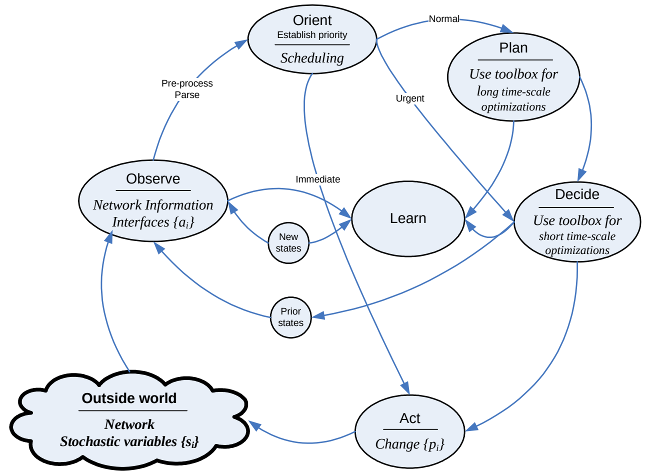

Fig. 1. Behavioural model of the cognitive radio and how the steps are realized using the proposed CRM (in part modified from [1]).

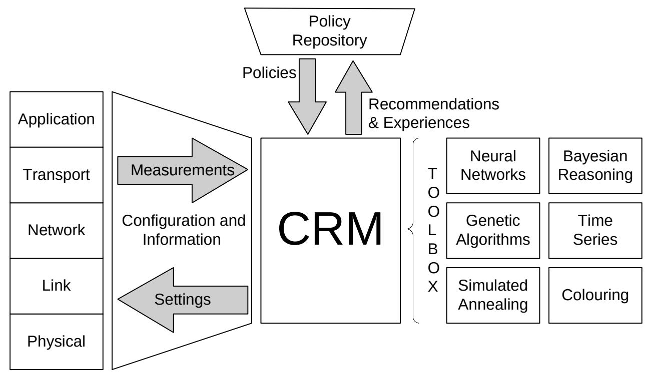

Fig. 2. Conceptual architecture of the CRM.

CRM as a multi-functional software entity that will primarily carry out cross-layer optimization using a *toolbox* of advanced reasoning methods and a great variety of information from the application layer, the underlying networking and data link layer as well as the operating system. Based on the collected knowledge the CRM can for example, optimally manage spectrum resources, flexibly adapt MAC and link parameters and allow the best possible settings for the applications running on top. In addition the CRM could consider policies such as proposed by the DARPA XG project [8] during all optimization processes. Later on the CRM can return its recommendations for policy updates based on experiences and observed behaviour of other network nodes.

We envision that the CRM can also function as a "connection manager" deciding upon the frequency channels as well as the type of communication technology to be used (IEEE 802.11, Bluetooth, UMTS, etc.) in case a variety of interfaces and networks are available. In this context, different services such as voice-call, audio- and video-conferencing can experience higher quality if their specific QoS requirements, e.g. in terms of delay and bit rate, are carefully taken into account.

Since the CRM will perform multidimensional optimizations using substantial amount of data, the traditional numerical methods might not be fast and scalable enough if applied to the full dataset. Accordingly, alternative approaches such as genetic algorithms and simulated annealing are used inside a toolbox as depicted in figure 2. These natural optimization methods are interesting candidates since they are proven to be successful in solving problems with large number of variables, can work with numerically generated or experimental data, and so on.

In order to more efficiently handle the large amount of knowledge data (including historical data), sorting and clustering of the available information used in the CRM is required. Classical techniques like *k-means* [9] can be considered, however due to the high degree of data variety and dynamicity, more advanced algorithms will be needed. Promising candidates include neural networks based approaches such as self organizing maps (SOMs) [10]. SOMs have already been successfully applied by us and others, e.g., to perform unsupervised traffic pattern classification and estimation without a priori information. Additionally, time series analysis can be used, for example, in finding periodicity and compensating for the missing data to be able to provide reasonable estimates.

In order to achieve a reliable operation of the CRM, quality of the data used in the decision process should be ensured. Accordingly, e.g., data filtering techniques to handle the linear and non-linear noise are required. Techniques such as Bayesian reasoning and statistical learning theory can be deployed to deal with uncertainty and ensure the reliability of the data and inference.

Although it is represented as a single block in the architecture, the CRM has a modular and extensible structure. For example, the toolbox itself is not limited to the enabling optimizing techniques mentioned above. Further methods could be added in a plug-and-play fashion. In fact, from an implementation point of view, the CRM could be seen as a micro kernel with additional software modules where the scheduling and time synchronization mechanisms of different optimization and reasoning processes are carried out. We intend to study this issue more. One of the key challenges for CRM is its distributed structure. If compared to the recent proposal of knowledge plane [6], the extra problem in our case is that CRM needs to work in real-time both as an observation and knowledge processing point.

III. Functions, APIs and Enabling Technologies

After we have introduced the CRM-concept we shall explain how we foresee the CRM to retrieve all the required information which is one of the major practical problems to be solved on the way towards cognitive wireless networks. This is also a domain where more stable intermediate research results have already been obtained. The CRM needs to be aware not only of the spectrum usage, the quality of available links and higher layer traffic information but also of the network topology and other nodes participating in the network. The former aspects are more focused on one node and how it sees its surroundings.

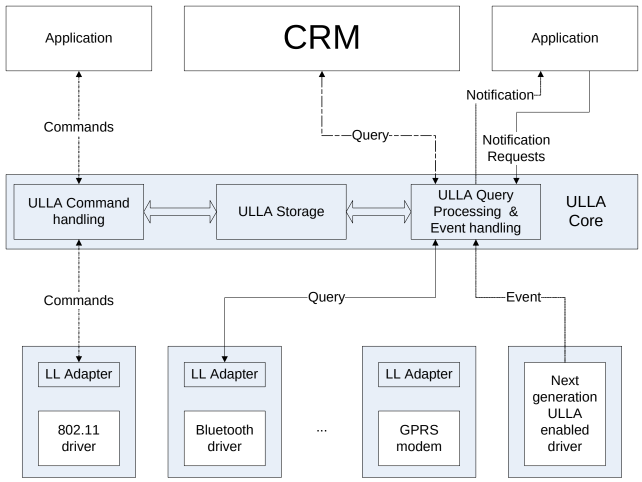

Fig. 3. Simplified architecture of ULLA.

However, this information is still difficult to obtain since the wireless world has become increasingly heterogeneous and the available interfaces to control and monitor networks have not kept pace. Hence, we see a Unified Link-Layer API (ULLA) as suggested by GOLLUM consortium [11] as one important enabler. It offers a common interface to manage wireless links and observe their performance, and is developed by the industry-academia collaborative project.

Figure 3 shows the simplified architecture of ULLA, which consists of applications or operating system agents such as the CRM that use ULLA to request information or register for notifications upon certain changes in the environment. This way the CRM can, for example, register for notifications for drastically decreasing performance on one link and if this occurs the CRM could quickly react and start one of the available optimization techniques. The ULLA core is the major block in the design that connects applications and network devices.

Since the CRM requires knowledge of the complete network stack a similar interface is needed for higher-layers in order to, e.g., solve the well-known interaction problems of TCP over wireless links or other cross-layer optimizations. In addition a direct interface between the CRM and applications would be helpful for negotiating QoS requirements. The CRM has the whole view of the ongoing communication and can estimate whether the requested QoS-level can be achieved. In the case of legacy applications the CRM will use time series analysis to extract such requirements during runtime and try to reconfigure the network stack accordingly.

The interfaces discussed above are, of course, purely local in nature. In mobile and wireless environments such a subjective view is not sufficient to optimize the overall network performance. Especially, fairness aspects but also basic problems such as the hidden node problem require a more complete view of the network. Communication peers that agree on working frequencies and synchronize on respective changes when primary users return are simple first steps in these directions. More extensive collaboration will enable nodes to know the whole network topology and avoid effects such as severe network overload using advanced rate adaptation or enable better understanding of transmission errors and possible countermeasures. Taking into account the toolbox described in section II collaborative information gathering allows distributed but global instead of local imperfect optimization.

Another major research challenge seems to be the large dynamic range of characteristic time-scales that are involved at different levels. Some of the processes have typical time granularity of μs, but the slowest periodic processes can reach time-scales of days. Our argument to see the CRM partially as a kernel is related to that challenge. We want to keep consistent time-sampling, task-scheduling and data-passing between different processing and learning phases.

IV. Conclusions

The poster discusses some early research results on the future directions and research challenges in cognitive radio domain, focussing on possible limitations of the present-day approaches. We presented the Cognitive Resource Manager (CRM) that is an enabling technology to build *cognitive wireless networks*. The CRM is a framework for optimizing network-wide radio resources and managing cross-layer optimizations with machine learning techniques and plug-and-play toolbox. The first presented findings were achieved in ARAGORN-project (Adaptive Reasoning and Ambient intelligence for Global Optimization in embedded Radio Networks) by RWTH Aachen.

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