Reconfigurations Selection in Cognitive, Beyond 3G, Radio Infrastructures

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Abstract. B3G (Beyond the 3rd Generation) wireless infrastructures can be efficiently realized by exploiting cognitive networking concepts. Cognitive, wireless access, infrastructures can dynamically configure their transceivers with the appropriate Radio Access Technologies (RATs) and spectrum, in order to, reactively or proactively, adapt to the environment requirements and conditions. Reconfiguration decisions call for advanced management functionality. This paper provides such management functionality by addressing a pertinent problem, called "*RAT and Spectrum selection, QoS assignment and Traffic distribution*" (*RSQT*). Our work contributes in four main areas. First, we formally define and solve a fully distributed problem version, which is very important for the management of a particular reconfigurable element. Second, we propose robust learning and adaptation, strategies for estimating (discovering) the performance potentials of alternate reconfigurations. Third, we give a computationally efficient solution to the problem of exploiting the performance potentials of reconfigurations and thus selecting the best ones. Finally, we present results that expose the behaviour and efficiency of our schemes.

Keywords. Cognitive networks, B3G wireless infrastructures, Utility, Learning and Adaptation, Autonomic computing, Seamless mobility

1. INTRODUCTION

Immense research and development effort is being dedicated to the development of new wireless networking technologies. This work delivers powerful and affordable, *high-speed*, *wireless access* solutions. Currently, the wireless access landscape includes a multitude of technologies available to the mean user. Moreover, the wireless world is migrating towards the era of B3G (Beyond the 3rd Generation) [**Error! Bookmark not defined.**] wireless access communications. The motivation is to increase the exploitation of the available technologies. The main idea is that a network operator (NO) can rely on different radio access technologies (RATs), for achieving the required capacity and QoS (Quality of Service) levels, in a cost efficient manner. The B3G concept can be realized through *cognitive* (adaptive, reconfigurable) networking potentials [1,2], in conjunction with network cooperation [3,4,5]. Cognitive networks, reactively or proactively, adapt to the environment requirements and conditions, in principle, by means of *self-configuration*. Self-configuration is applied, for tackling complexity and scalability. Reconfiguration may affect all layers of the protocol stack, namely, the physical, MAC (Medium Access Control) and LLC (Logical Link Control), network, transport, middleware and application layers. Specifically, as part of the reconfiguration, at the physical and MAC layers, there can be elements (hardware components, such as transceivers) that *dynamically change the RATs they operate and the spectrum they use*, in order to improve capacity and QoS levels. In this respect, it is believed that cognitive networks enable the realization of B3G infrastructures with reduced capital expenditures (CAPEX).

The realization of cognitive, wireless access, networks requires advanced *management functionality*, which will be in charge of finding the best reconfigurations. This paper provides such management functionality, by addressing an important problem for the management of a reconfigurable network element, which operates and is managed in parallel with other elements. The problem is called "*RAT and Spectrum selection, QoS assignment and Traffic distribution*" (*RSQT*). Capabilities are exploited in the provision of the highest possible QoS levels, at the appropriate capacity levels. This exploitation yields a rating of the candidate reconfigurations, and leads to the selection of the best one.

The organization of the paper is as follows. Section 2 presents the main features of a cognitive wireless access infrastructure. Section 3 defines the RSQT problem, and outlines the two main parts of its solution. Section 4 describes the first main part of the RSQT solution, i.e., the robust (stable) methods for estimating the performance of reconfigurations. Section 5 is the second part of the RSQT solution, which is a computationally efficient algorithm to the problem of exploiting the capabilities of reconfigurations, as well as rating and selecting the best reconfigurations. Section 6 provides results that show the behaviour and efficiency of our schemes, and section 7 includes concluding remarks.

2. COGNITIVE, WIRELESS ACCESS INFRASTRUCTURES

Cognitive network segments complement the B3G infrastructure. Traditional approaches either load a set of pre-defined configurations, or use a policy server to dole out policies as appropriate. Our method improves these approaches by enabling each element of the segment to *dynamically* select its configuration.

In this context, each element selects the appropriate RATs and spectrum. Specifically, each element is controlled by management functionality that detects changes in the environment and user needs, and reconfigures the element to maintain its business objectives. Cognitive segments can change (reconfigure) their transceivers operating RATs and frequencies in different time zones, so that to better adapt to environmental stimuli. Changes are performed online and do not exclude the potential introduction of completely new technologies. However, while the cognitive element can employ multiple technologies, all the technologies are not operated simultaneously. Only the appropriate technologies are selected, activated and used, based on context. Moreover, the fact that the reconfiguration of transceivers can change in time and space is important, as it enables the system to *track and respond appropriately to changes in the environment and/or user needs*. Reconfiguration decisions require advanced management functionality, which is the main subject of this paper.

3. RSQT PROBLEM STATEMENT

RSQT is seen as a main part of the management functionality required for taking reconfiguration decisions in the context of cognitive infrastructures.

3.1. RSQT input

The input is classified in four categories: (i) element capabilities, (ii) service area requirements, (iii) discovery, and (iv) profiles and agreements.

Element capabilities. This part provides information on the candidate configurations of the element, such as the set of available transceivers that will be capable of operating a set of RATs and the set of spectrum carriers with which RAT r can be operated. Each transceiver has a set of candidate configurations, i.e. combinations of RATs and spectrum.

Service area requirements. This part exploits basic monitoring information for estimating traffic requirements and mobility characteristics in the service area. This includes the users in the service area and the services requested.

Discovery. This part exploits basic monitoring information for estimating the capabilities (capacity and coverage) of the candidate configurations.

Profiles and agreements. This part describes the profiles (e.g., preferences, requirements, constraints) of user classes, applications and terminals, as well as the policies and agreements of the NO.

3.2. RSQT output

The reconfiguration decisions fall into three main sets: (i) transceiver reconfiguration; (ii) QoS assignment; (iii) traffic distribution.

Transceiver reconfigurations. These denote the allocation of a certain configuration to each transceiver. This fully complies with the element capabilities (i.e., permissible allocations of RATs and spectrum to transceivers).

QoS assignment. This is associated with the allocation of applications to QoS levels.

Traffic distribution. Finally, users are allocated to transceivers. This is aligned with the provision of applications through permissible RATs, in accordance with the (terminal) profiles, NO policies and agreements.

Objective function. The reconfiguration decisions should optimise an objective function that consists of two main parts. (i) The first part is targeted to the maximisation of the aggregate utility volume. The rationale is that users should be assigned to their most preferred QoS levels, to the largest extent possible. (ii) The second part of the objective function is targeted to the minimisation of the number of required changes. These changes are seen as the cost of reconfiguring the element. The rationale is that among reconfigurations that exhibit the same performance, those that require fewer changes should be preferred.

4. ROBUST DISCOVERY OF RECONFIGURATION CAPABILITIES

This section presents the learning and adaptation method for robustly estimating the likelihood that reconfiguration c is associated with capacity $cp_e(c)$ and coverage $cv_e(c)$.

4.1. Formulation through Bayesian networks

Figure 1 depicts a Bayesian network that is proposed for modeling the specified problem.

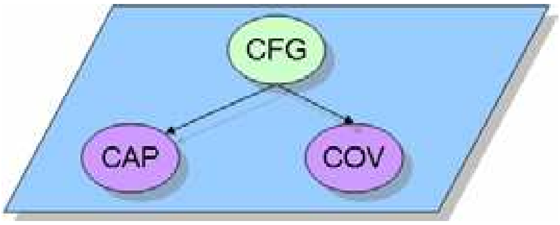

Figure 1: Bayesian Network

CAP and COV are random variables representing capacity and coverage, respectively. CFG is another random variable representing a configuration, e.g., we can have $CFG = c = (r, f)$. The goal is the computation of the maximum value of the joint conditional probability $\Pr[CAP, COV|CFG]$. The desired probability $\Pr[CAP, COV|CFG]$ is equivalent to the computation of the product of the conditional probabilities $\Pr[CAP|CFG]$ and $\Pr[COV|CFG]$, i.e.

$$\Pr[CAP, COV|CFG] = \Pr[CAP|CFG] \cdot \Pr[COV|CFG] \qquad (1)$$

4.2. *Solution: learning and adaptation*

Let us assume that measurements (obtained through basic discovery-sensing functionality) show that a specific configuration can achieve capacity cap_{meas}. Additionally, let $dif_{\max}$ be the maximum difference between the probable capacity values, i.e., $dif_{\max} = cap_m - cap_1$.

Then, the following correction factor, cor_i, can be computed for each candidate capacity value cap_i:

$$cor_i = 1 - \frac{|cap_i - cap_{meas}|}{dif_{\max}} \qquad (6)$$

It holds that $0 \leq cor_i \leq 1$. A value close to 1 reflects that the corresponding candidate value cap_i is close to the measured value cap_{meas}, thus it should be reinforced accordingly. The opposite stands for a value close to 0.

The correction of the $\Pr[CAP = cap_i|CFG]$ values can then be done as follows for each candidate capacity value cap_i:

$$\Pr[CAP = cap_i|CFG]_{new} = nf \cdot cor_i \cdot \Pr[CAP = cap_i|CFG]_{old} \qquad (7)$$

The parameter nf is a normalizing constant whose value can be computed by requiring all the "new" probabilities to sum up to 1.

The system *converges* when the most probable candidate capacity value (i.e. the one with the maximum probability) is reinforced, while the probabilities of the other candidate capacity values are either reduced or reinforced less. After convergence, we limit the number of consecutive updates that can be done on the probability values associated with each capacity value. This is done for assisting fast adaptation to new conditions. For the same reason, we do not allow that a probability falls under a certain threshold, a/m, where $0 < a < 1$ (m is the number of potential capacity values). In such cases, the normalization factor, nf, is computed by requiring all the other "new" probabilities to sum up to 1-($k \cdot a/m$), where k is the number of probabilities that are assigned equal to the threshold.

5. SELECTION OF RECONFIGURATIONS

This section exploits the potential capabilities of candidate reconfigurations. This yields a rating of reconfigurations, and eventually, leads to the best reconfigurations. In general, this part of the solution of the RSQT problem consists of four phases (Figure 2).

The first phase finds different valid transceiver reconfigurations, each one consisting a sub-problem, subject to parallel processing.

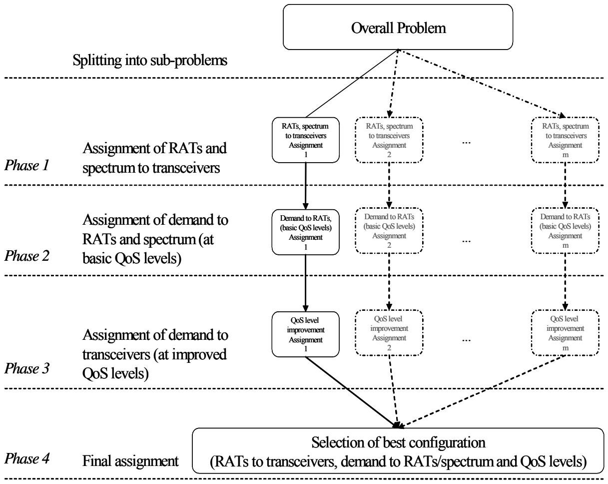

Figure 2:Strategy for the solution of the problem

In the second phase, in each of the sub-problems, the demand distribution, is computed. At this phase, the QoS levels offered to users are kept to their lowest acceptable values. If a solution cannot be provided under these conditions, the reconfiguration is rejected.

Then, in the third phase, the QoS level offered to users is gradually improved, until either no further increase is possible (users are at the maximum QoS level) or there is no more capacity available.

Essentially, the previous phases provide a rating of reconfigurations, with respect to the objective function. So the last, or fourth, phase selects the best reconfiguration, i.e., the reconfiguration with the highest objective function value.

6. RESULTS

This section presents results on the reconfiguration selection methods.

A simple service area is covered by a network segment. The segment consists of a number of reconfigurable elements. Elements operate in parallel. The behaviour of these elements and the service area requirements cause reconfiguration triggers, which will be in the focus of this subsection. The demand in the element's service area includes nine different cases studied, each one corresponding to a different traffic mix (combination of voice and data sessions). Initially, the demand for voice dominates. Gradually, the demand for the data service dominates. The demand is taken uniformly distributed within the service area.

Each element is equipped with 3 reconfigurable transceivers. Each transceiver may select between two configurations. In doing so, the resulting overall configurations for each element can be denoted as e.g. (c_1, c_1, c_2), implying that two transceivers are assigned configuration c_1, while the third one is assigned configuration c_2 and so forth. Additionally, the assignment of configuration c_2 to all transceivers is not considered, since it would lead to coverage holes. As aforementioned, the configurations c_1 and c_2 have different capacity capabilities, 1 or 2Mbps for c_1, and 4, 7 or 10Mbps for c_2. It is also assumed that c_1 can achieve larger coverage than c_2, i.e., the larger the capacity is, the smaller the coverage becomes.

Finally, two services are available, a voice service (s1) and a data service (s2). Whereas the voice service is associated with a fixed quality level, for the data service, a set of quality levels is provided. Moreover, s1 can only be offered through configuration c_1.

All in all, we are able to make scenarios, combining the capabilities (capacity and coverage) of the configurations, in order to see which configuration fits better the traffic mixes. Such a scenario would assume that $cp_e(c_1)$=1 Mbps and $cp_e(c_2)$=4 Mbps. The coverage pattern for c_1 is about 1000m, and for c_2 about 500m. Figure **3** shows indicative results.

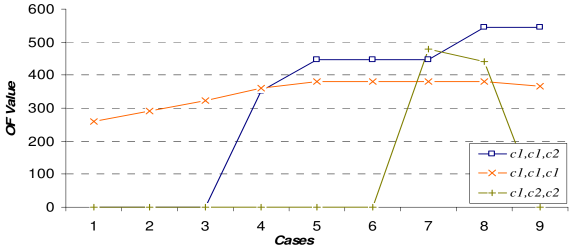

Figure 3: Scenario 1 - Results

Configuration (c_1, c_1, c_1) increases the objective function value as the data load increases. This happens because, at the same time, voice load decreases, and therefore, there is spare capacity that can be exploited in offering higher QoS to more data sessions. At some point, the objective function value remains the same (cases 5-8), since the increase deriving from new data sessions is compensated by the decrease in the voice sessions. Finally, in case 9, the data sessions have become so many, that for some users the QoS levels offered need to be degraded, compared to case 8, and thus, the objective function value decreases.

The behaviour of the (c_1, c_1, c_2) configuration is similar. Initially (cases 1-3), the configuration cannot handle the demand, because the voice load dominates and exceeds the capacity of the two c_1 transceivers. Starting from case 4, the voice sessions have decreased and can be accommodated by the two transceivers, configured with c_1. Consequently, (c_1, c_1, c_2) yields the highest objective function value. This occurs since the spare capacity is exploited for providing higher QoS to data services. Higher objective function values are achieved, compared to (c_1, c_1, c_1), because $cp_e(c_2)$ is higher. At some point the improvement stops, because the overall load is heavy, and therefore, some of the QoS levels have to be degraded again.

Finally, configuration (c_1, c_2, c_2) exhibits an acceptable performance only at certain traffic mixes. Specifically, its objective function value is initially zero, until the voice sessions can be accommodated by a single c_1 transceiver. This occurs in case 7. Then, (c_1, c_2, c_2) proves itself to be appropriate, but only until the data sessions have become far too many and cannot be catered for by c_2's limited coverage (the distribution of users within the element is uniform).

Comparing now the alternatives, we find that at the very initial demand patterns, the (c_1, c_1, c_1) configuration performs better. However, as data sessions increase, the

(c_1, c_1, c_2) configuration becomes superior, due to the spare capacity that can upgrade QoS levels offered to continuously coming data sessions. This excellence of (c_1, c_1, c_2) is though sometimes marginal compared to (c_1, c_1, c_1). Additionally, at certain traffic mixes with few voice and many data sessions, (c_1, c_2, c_2) exhibits the best performance, due to its large overall capacity.

7. CONCLUSIONS

B3G wireless infrastructures can be efficiently realized by exploiting cognitive network concepts. Cognitive, wireless access, infrastructures dynamically reconfigure to the appropriate RATs and spectrum, in order to adapt to the environment requirements and conditions. Reconfiguration decisions call for advanced management functionality. This paper provided such management functionality by addressing a pertinent problem, called "RAT and Spectrum selection, QoS assignment and Traffic distribution" (RSQT). We formally defined and solved a fully distributed problem version. We proposed robust (stable, reliable), learning and adaptation, strategies for estimating (discovering) the performance potentials of alternate reconfigurations. We gave a computationally efficient solution to the problem of exploiting the performance potentials of reconfigurations, and presented results that expose the behaviour and efficiency of our schemes.

One of our future plans is to further employ autonomic computing principles in the direction of realizing cognitive, wireless access, infrastructures. Our goal is to develop an autonomic manager, which will encompass the RSQT scheme. The manager will consist of policies, context perception capabilities, reasoning algorithms, learning functionality and knowledge engineering, technologies for the representation of ontologies and semantics. All these will yield a system that *hypothesises* on causes to a problem, and subsequently, validates or falsifies the hypothesis.

Another issue for future study is to complement the distributed RSQT scheme with a second tier of, more centralised, management functionality. The centralised functionality will be invoked when the distributed components cannot converge to acceptable solutions. The synergy of the two tiers will guarantee that whenever the distributed components diverge from the near-optimal performance levels, the application of the second tier will restore the performance to the desired levels.

Another issue for further study is to exploit the RSQT scheme for enabling NOs to *personalise* their service offerings, instead of limiting subscribers to a fixed set of inflexible choices. Seamless mobility applications can build on schemes like RSQT to intelligently change the services that they provide based on business policies and context.

8. REFERENCES

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