Architecture and Signaling Protocol for Migration to Cognitive Reconfigurable Post-3G Mobile Systems

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The advent of software-defined radio products and recent advances in cognitive radio research will facilitate the preservation or even improvement of user perception in volatile radio conditions while optimizing the use of network resources. Based on cognition techniques, the autonomic communication paradigm attempts to pave the way towards self-governed systems that will alleviate the shortcomings of present remotely managed user devices. This article identifies the challenges for such cognitive reconfigurable systems and introduces CORPS, a new end-to-end architecture that unifies software and cognitive radio themes enriched by self-ware capabilities. The manuscript discusses the adopted network-agnostic protocol-independent modeling approach, which is in line with best common practices in the industry, and presents the system architecture in terms of functional specification and UML modeling. Next, the CORPS functional architecture is mapped to the evolved-UMTS system under development in 3GPP. Finally, the paper proposes and evaluates CREST, a novel signaling protocol for improving the quality of service of existing bearers in a post-3G network through radio-access-technology switching and coordinated dynamic spectrum access.

I. Introduction

Next-generation mobile networks will integrate emerging wireless personal (e.g., Ultra-WideBand, ZigBee), metropolitan (e.g., IEEE 802.16 series), and regional access networks (e.g., IEEE 802.22) into present cellular, broadcast, and Wi-Fi air interfaces. Global initiatives such as the Third Generation Partnership Project (3GPP) have been working on the long-term evolution (LTE) of air-interfaces and supporting architectures, setting high-level requirements and focusing on the support of IP-based services through various access technologies, thereby targeting seamless mobility between heterogeneous access-networks [1]. The major research challenges for such adaptive communication systems are a) inter-system handover, b) discovery and selection of new access systems based on operator policies, user preferences, and knowledge of ambient radio conditions, and c) maintenance of the negotiated end-to-end quality of service (QoS).

Software-Defined Radio (SDR) [2] and Cognitive Radio [3,4] have been the subject of intensive research in the telecom community, aiming to upgrade the capabilities of equipment according to user requirements and network conditions, and to fully exploit the available spectrum resources temporally and spatially. On the other hand, the administration and management of complex information systems comprises a significant part of the overall operational expenditure that has raised the need for self-management in computing and networking. Autonomic computing emerges as a new paradigm for managing increasingly complex tasks at the business, system, and device level without human intervention [5]. Autonomics is an umbrella term for open user-agnostic capabilities and behavior of an entity focusing on self-configuration (the ability to automatically setup and (re)adjust the configuration of parameters and resources according to external stimuli). This broad research area spans self-healing (ability to discover potential malfunctions and recover from failures), self-optimization (ability to optimize the performance of executed tasks based on experience), and self-protection (ability to ensure overall security and integrity), thus yielding the so-called “self-CHOP” capabilities.

While the IT community has been struggling to identify technical solutions for this new epoch, research efforts propose the adoption of the autonomic computing principle in communication systems, fo-

Appears in *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 12, no.4, pp. 15-31

cusing on self-governance aspects and dynamic assembly and adaptation of policy rules [6]. Additional capabilities include self-knowledge (ability to know the status of its own resources, components, and communications), self-adaptation (ability to adapt its behavior to given stimuli), and self-organization [7]. Conversely, the aforementioned computing-initiated self-CHOP capabilities provide the way-to-go from the telecom-initiated faults, configuration, accounting, performance, security (FCAPS) functions [8] to flexibly governed (rather than managed) systems.

In [9], we focused on the network support architecture for the coordination of SDR-oriented operations, and discussed software download over reconfigurable radios. The present article envisages cognitive reconfigurable post-3G networks as the paradigm of heterogeneous beyond 3G mobile systems that bridge SDR and cognitive radio, and enhance user equipment (UE) and network elements with intelligence to make autonomous decisions. Such decisions target the improvement of quality of service through two mechanisms: switching to a new radio access technology and/or hopping to a vacant spectrum band.

The paper is structured as follows: The next section highlights the technical challenges and discusses the adopted modeling approach. Section III introduces the *COgnitive Reconfigurable Post-3G System (CORPS)* architecture in terms of system and functional capabilities specification and platform-independent modeling in the Unified Modeling Language (UML) [10]. The mapping of the CORPS architecture to the 3GPP System Architecture Evolution (SAE) framework is elaborated in section IV. Section V proposes the *Cognitive REconfiguration Signaling proTocol (CREST)*, a new signaling protocol for improving the quality of service of ongoing connections in cognitive reconfigurable systems. This section also highlights how the proposed protocol operates around the well-known cognition cycle in a post-3G environment. Section VI gives analytical expressions and evaluates the proposed CREST signaling through numerical results. Comparison with related protocols can be found in section VII, with conclusions and directions for future work delineated in section VIII.

II. Cognitive Reconfigurable Systems: Challenges and Modeling Approach

A. Challenges and Innovation

Reconfiguration is a set of policy-driven tasks for modifying the operation and behavior of systems, network nodes, and capabilities of functional elements. In the short term, end-user devices and base stations will be reconfigured; it is expected that, in the long-term, interior network elements will also have to be dynamically upgraded in order to ensure homogeneous resource adaptation of the end-to-end data path. Interpreting the end-to-end perspective [11] in mobile communication systems, user and control plane interactions can occur from source to destination in order to adapt the system operation and modify the operational mode of equipment and software modules.

This article identifies the following problems in present systems:

- How to migrate from the restricting centralized client-server-based decision-making relationship between mobile terminals and the network infrastructure.
- How to facilitate dynamic upgrades of equipment capabilities and expedite the time-to-market, instead of having pre-installed features during manufacturing time.
- How to exploit context-awareness and the available radio-network resources in the vicinity of a mobile terminal.
- How to integrate a set of architectural modules in a flexible fashion that alleviates legacy monolithic modeling approaches and achieves distributed operation.

The system architecture proposed in this paper recommends a solution to the first problem through innovative self-governance and self-configuration capabilities. This goes beyond the traditional policy model in 3G mobile communications [12] where a network policy-server controls a number of user terminals in a client-server fashion. Instead, this manuscript proposes that the terminals be allowed to define their own local policies based on experience and current conditions, govern the (re)configuration procedures without external administration, and make autonomous decisions. Furthermore, the overall system operates around a feedback loop, thereby migrating to cognitive behavior.

The second problem is addressed through software downloads that allow dynamic replacement of radio-software and related protocols. The third challenge is fulfilled via a new strategy and signaling protocol for improving the quality of service of ongoing connections through switching between access technologies and/or dynamic spectrum negotiation, allocation, and access.

The key strength of the proposed architecture lies in the unification of behavioral and structural aspects of systems that bear features from three technical areas, i.e., autonomic communications, SDR, and cognitive radio. To this purpose, the present work solves the last problem through modular introduction of additional capabilities based on a staged methodology that offers fine-grained abstraction levels. Basing the modeling work on such principles benefits from flexible mapping of functional entities to network configurations, allowing for independent evolution paths and refinements of the legacy infrastructure.

B. Modeling Approach and Scope

The architecture is built in line with best common practices in modeling complex systems. Two key standardization methods form the basis of the evolution-centric approach adopted in this work: the 3GPP Integration Reference Point (IRP) specification stages [13] and the Object Management Group (OMG) Model-Driven Architecture (MDA) [14].

3GPP IRP comprises a three-level specifications approach: The *Requirements* level provides conceptual and use-cases definition; the *Information Service* level provides technology-independent specifications; the *Solution Set* level provides technology-specific solutions through designated protocols to realize the claimed functionality. The Information Service level is further decomposed to the following abstraction levels:

- The *Interface IRP* provides an abstraction at the level of network-agnostic protocol-independent modeling of procedures and signaling.
- The *Network Resource Model IRP* introduces the network domain dimension, whilst keeping an abstraction at the level of protocol independence.
- The *Data Definition IRP* provides the parameter definition and reuses the already-defined Interface and Network Resource Model IRPs.

Similar to the 3GPP IRP approach, OMG MDA separates between a platform-independent model that is agnostic to the underlying middleware and hardware platform, whereas allowing a plethora of platform-specific models. The latter are introduced by picking up designated languages, protocols, operating environment, and physical data to realize the specified functionalities.

This work covers all stages of the 3GPP IRP methodology, thereby accommodating different levels of abstraction as a means to simplify architecture specification problems. Firstly, the high-level system capabilities proposed below comprise the Requirements level. Secondly, these system capabilities are used as a guideline to derive the functional entities that bear detailed functional capabilities, thereby yielding the Interface IRP in the form of novel functional and UML models. Next, the mapping of the functional entities to physical network configurations produces an innovative Network Resource Model IRP for cognitive reconfigurable post-3G mobile systems. Finally, the manuscript proposes a new signaling protocol with specific information elements, which comprise the Solution Set and Data Definition IRPs, respectively.

III. CORPS Architecture

A. System Capabilities and Derivation of Functional Entities

Table 1 aggregates the key evolutionary technical aspects that stimulate the formulation of new high-level capabilities of cognitive reconfigurable systems. The paper proposes the following primary *system capabilities* offered by cognitive reconfigurable post-3G networks:

1. Smart selection of Radio Access Technology/Network (RAT/RAN) through autonomous decisions by the user equipment.
2. Upgrades of equipment capabilities through over-the-air software-downloads in conjunction with device self-configuration. This capability usually involves the reconfiguration of physical resources and operating parameters (e.g., power, modulation type).
3. Negotiation of spectrum resources and dynamic spectrum allocation and access.

The first system capability raises the need for an overarching functional entity that collects the ambient knowledge, makes appropriate decisions based on such intelligence, orchestrates all reconfiguration operations, and dynamically generates new policy rules without direct guidance from external policy servers. We hereafter call this entity *Self-Governance Function* (*SGF*).

The second system capability dictates the introduction of functional entities responsible for a) downloading and installing the appropriate radio-software (namely the *Software Download Function, SDF*), and b) self-configuring the device and adapting the allocated resources to the new operating conditions (hereafter called *Self-Configuration and Resource management Function, SCRF*).

The third system capability requires a dedicated functional entity that negotiates the transfer of

Table 1. Main evolution axes for the formulation of cognitive reconfigurable post-3G systems

RAT/RAN evolution *IEEE standards*: WPAN (802.15.3a, 802.15.4) WLAN (802.11-2007/k/n/r/v) WMAN (802.16a/d/e/h (WiMAX)), WRAN (802.22) Media-Independent Handover (802.21) *3GPP air interfaces*: LTE Super 3G HSPA MBMS *3GPP LTE requirements*: Multi-RAT support Self-configuring RANs Flexible functional split between RAN and core network Higher data rates with reduced latencies Increased spectral efficiency Lower power consumption at the terminal equipment *Proprietary solutions*: ArrayComm i-Burst Qualcomm Flarion FLASH-OFDM DoCoMo 4G 5 Gbps (field experiment)	**Core network & service domain evolution** *3GPP SAE:* Efficient network access selection according to operator policies and user preferences Seamless inter-access mobility Support of reconfigurable radio interfaces in the terminal *3GPP IMS:* Session-based core network architecture using SIP: the next-generation core network paradigm for service provision to wireless devices *ETSI TISPAN NGN:* System enhancements to IMS for fixed broadband access: Network attachment subsystem Resource and admission control subsystem **Software-Defined Radio & Cognitive Radio** *SDR Forum:* Equipment upgrades through over-the-air radio-software download *OMG SBC:* MDA PIM/PSM for Software Radio Components (P^2SRC) *Cognitive Radio:* IEEE SCC41 (dynamic spectrum access networks) / P1900.1, .2, .3, .4, .5 (spectrum management, SDR/CR-oriented standards) ETSI TC RRS
Autonomic Communications *ITU-T TMN FCAPS:* Managed network elements (usually network-initiated) ⇒	*Self-CHOP:* Governed autonomic communication elements

spectrum usage rights, allocates spectrum bands, and executes decisions to jump to unoccupied frequencies (hereafter called *Spectrum Negotiation and Allocation Function, SNAF*).

In order to achieve the aforementioned tasks, the architecture should accommodate auxiliary functional entities for retrieving and processing contextual information and interpreting the acquired knowledge. Specifically, distinct functional entities should a) introspect the reconfigurable element (i.e., monitor the status of the device) (*Performance Monitoring Function, PMF*), and b) sense the surrounding environment, discover the system capabilities offered by the available networks, negotiate QoS attributes, and process the collected profile information (*Capabilities Discovery Function, CDF*).

Figure 1 depicts the identified functional entities of the CORPS architecture and related interfaces. The following section delves into the details of the functional capabilities that each functional entity accommodates, with Figure 2 illustrating the corresponding platform-independent model in UML. This model collects all the functional capabilities in the form of UML operations and attributes, thereby highlighting the innovative structural and behavioral features of the architecture.

B. Description of Functional Capabilities

The *Self-Governance Function (SGF)* orchestrates all reconfiguration operations, and is responsible for

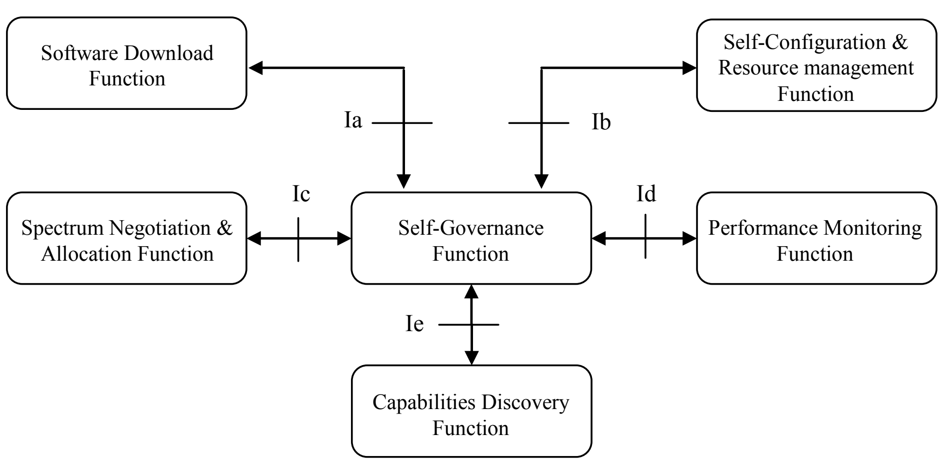

Figure 1. Functional entities of the CORPS architecture

producing definitive decisions on actions to be executed and enforced by other functional entities. It consists of two sub-functions: the *Autonomic Decision-Making* and the *Policy Control* sub-function. The former assembles and authorizes converged actions based on the aggregation and filtering of a wide range of policy rules delivered by the latter sub-function. In addition, it initiates the negotiation of QoS attributes of ongoing connections. For this purpose, it triggers a number of negotiation control loops with control servers (e.g., the mobility anchor in cellular systems) in order to exchange their capabilities prior to the reservation of resources or before a candidate operational-mode switch. Self-governance lies in the ability to define additional policies autonomously due to contextual information and previous experience. Besides, the policy control sub-function retrieves, updates, and revokes existent policy rules. Local policies and policies with short lifetime are cached, therefore alleviating the need for frequent communication with external policy repositories.

The *Software Download Function (SDF)* handles the steps that follow the discovery of the system capabilities offered by the network, and the negotiation of QoS attributes (both are CDF tasks and will be explained later). Specifically, this function coordinates the actual transfer of the downloadable software as well as local procedures at the UE such as software validation and activation and in-situ testing. In addition, the SDF executes the transition from a unicast software-download mode to a multicast or broadcast mode, depending on the directives given from the SGF. The transition from one-to-many to one-to-one software-download mode or vice-versa can also be triggered by the PMF based on the analysis of monitoring reports.

The *Self-Configuration and Resource management Function (SCRF)* is responsible for the online configuration of the autonomic element without external provisioning (e.g., from the operations & maintenance system). This includes procedures for substituting protocol versions and software components, recompiling the protocol stack, and switching to a new RAT (with or without restarting the device) when inter-RAT handover has been decided by the SGF. Besides, the SCRF can be triggered by the PMF to take corrective measures when the overall

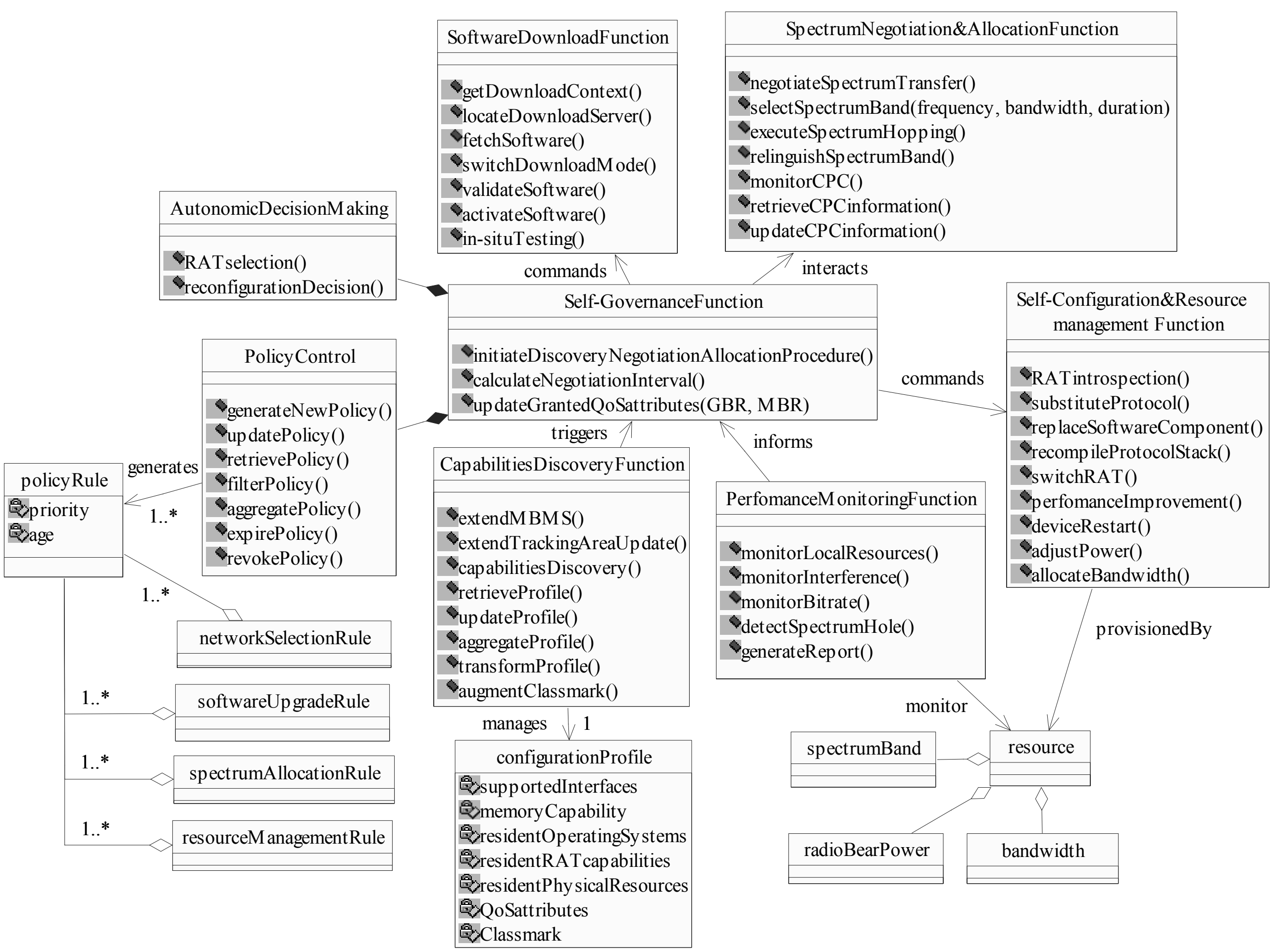

Figure 2. Functional capabilities of cognitive reconfigurable systems in the form of a platform-independent UML model

performance of the device falls below acceptable limits. In addition, this function executes resource allocation commands (e.g., bandwidth allocation) as requested by the SGF due to, for example, ongoing resource reservation signaling.

The *Spectrum Negotiation and Allocation Function (SNAF)* is responsible for a) participating in spectrum-transfer negotiation schemes (between base stations or access systems for intra- and inter-system spectrum transfer, respectively), b) allocating spectrum bands and executing spectrum hopping commands, and c) injecting/extracting information to/from physical or logical control channels that convey spectrum-related information. An example of such channel is the *Cognitive Pilot Channel (CPC)* [15] developed in the context of the EU-funded project E^2R II [16], which is envisaged as a radio enabler for reconfiguration by conveying a directory of the RANs, RATs, and frequencies offered in specific locations. In order to avoid a worldwide deployment of such a channel, the transport bearers of already-deployed air interfaces can be reused.

The *Performance Monitoring Function (PMF)* monitors resources that are provisioned or controlled by the SCRF and the SNAF. The generated performance reports are used for the adaptation and optimization of the autonomic element's behavior and performance, and can be exploited by other functional entities depending on the reconfiguration stage. For example, the SDF can use a performance report to optimize the downloading of large software patches.

The *Capabilities Discovery Function (CDF)* discovers the system capabilities (i.e., smart network selection, software upgrades, and dynamic spectrum access) that can be offered to an autonomic device in a post-3G cognitive environment. The system capabilities can be discovered in the following ways:

- The device can subscribe to the Multimedia Broadcast/Multicast Service (MBMS) [17], which will convey the necessary information about the reconfiguration possibilities in the designated area.
- Alternatively, this is feasible through an extension of the tracking-area update procedure, which is used for tracking the movement of idle-state UEs, and is invoked either periodically or whenever the UEs cross the borders of the tracking area. Cell updates can be used for active-state UEs.
- An example of lower-layer solution is through the CPC, which is one of the tasks of the SNAF, as explained earlier.

Furthermore, the CDF includes functionality so that the autonomic element can discover and negotiate the modification of QoS attributes. All this information from negotiation and discovery activities is handled by the CDF, which updates, aggregates, and transforms the capabilities of candidate RATs, terminal equipment profile (processing, memory, power, software and hardware environment capabilities), and QoS attributes of ongoing connections. The CDF evaluates all profile information and augments the UE classmark; the additional parameters label the capabilities of an autonomic element in terms of granularity of supported reconfiguration actions. For example, a device that requires restarting after a RAT reconfiguration is tagged with a different classmark than a device that is capable of real-time switching to the new RAT-configuration without a system reboot.

IV. Mapping to 3GPP Network Architecture

Figure 3 depicts the distribution of CORPS functional entities to the 3GPP SAE network for autonomously reconfigurable user equipment. This section first gives an overview of the main SAE elements. Next, the mapping criteria are explained, and detailed description of the CORPS-enhanced SAE network follows.

A. Overview of 3GPP System Architecture Evolution

The evolved 3GPP system consists of the UE connected to one or more evolved radio access networks, and evolved RANs connected to one or more evolved packet core networks. The latter provide connectivity to external Packet Data Networks (PDNs). The evolved RAN consists of a number of evolved Node-B's (eNBs), whereas the evolved packet core consists of the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the PDN Gateway (P-GW). Other key elements are the Home Subscriber Server as well as 3GPP service-stratum systems/functions such as the Policy and Charging Rule Function (PCRF), the Application Function, the Broadcast/Multicast Service Centre (BM-SC), and the IP Multimedia Subsystem.

SAE targets the long-term evolution of the 3GPP access technology for ensuring competitiveness in the next ten years [1,18]. The focus will be on the support of IP-based services through various access technologies, offering seamless mobility between heterogeneous access networks. However, the evolved 3GPP system neither captures software and cognitive radio aspects nor accommodates facilities for self-configuration and self-governance of the UE. The CORPS architecture attempts to cover this gap. The following paragraphs describe in brief the present capabilities of SAE elements and explain how these elements are enhanced with the CORPS functional entities.

B. Criteria for Mapping to Evolved 3GPP System

The mapping process is based on the following criteria and principles. Firstly, it tries to take advantage of existing network elements in order to minimize the impact on system deployment and to achieve a non-disruptive migration. For example, the PCRF already accommodates policy control functionality; therefore, it is advisable to avoid introducing a separate element for policy-based reconfiguration management. In the same fashion, the BM-SC encompasses functionality for broadcasting/multicasting information to the UE. Conversely, the introduction of negotiation signaling and additional reconfigurability-induced profile parameters should take advantage of the SAE distinction between mobility management elements and serving/PDN gateways. On the other hand, this paper proposes that novel capabilities be embedded into a new network element that acts as the anchor for the user equipment in a post-3G cognitive reconfigurable environment, hereafter called *Anchor CORPS Node (ACN)*. With this approach, the otherwise mandatory enhancements of existing SAE elements are minimized, and only one new interface between the ACN and the serving/PDN gateway is needed (based on the existing SGi interface). Details on the distribution of functional entities to SAE elements follow.

C. Enhanced 3GPP SAE Network for Cognitive Reconfigurable User Equipment

1) Cognitive Reconfigurable UE

The UE is a full-fledged CORPS-enhanced device incorporating the whole set of functional entities. It should be noted that the SGF and SCRF are not mapped to any network elements, as this figure depicts autonomously reconfigurable UEs. Therefore, decision-making for reconfiguration is solely a UE task without guidance from network elements, such as the PCRF or the ACN. In addition, self-configuration actions are executed only at the UE.

2) Evolved Node B

The evolved node B manages radio resources (e.g., packet scheduling in the downlink, radio admission control), and performs radio link control and policing of uplink user-plane traffic.

The eNB is enhanced with the SDF and SNAF. Through the SDF, the eNB is capable of downloading and operating multiple radio access technologies simultaneously. The SNAF participates in spectrum transfer procedures between base stations, responds to spectrum queries by the ACN SNAF, rearranges the spectrum, and injects information on the available RANs, RATs, and spectrum bands into the CPC.

3) Mobility Management Entity

This entity consists of functions for non-access stratum signaling, inter-core-network-node signaling for intra-3GPP-access mobility, establishment of dedicated bearers, management of tracking areas,

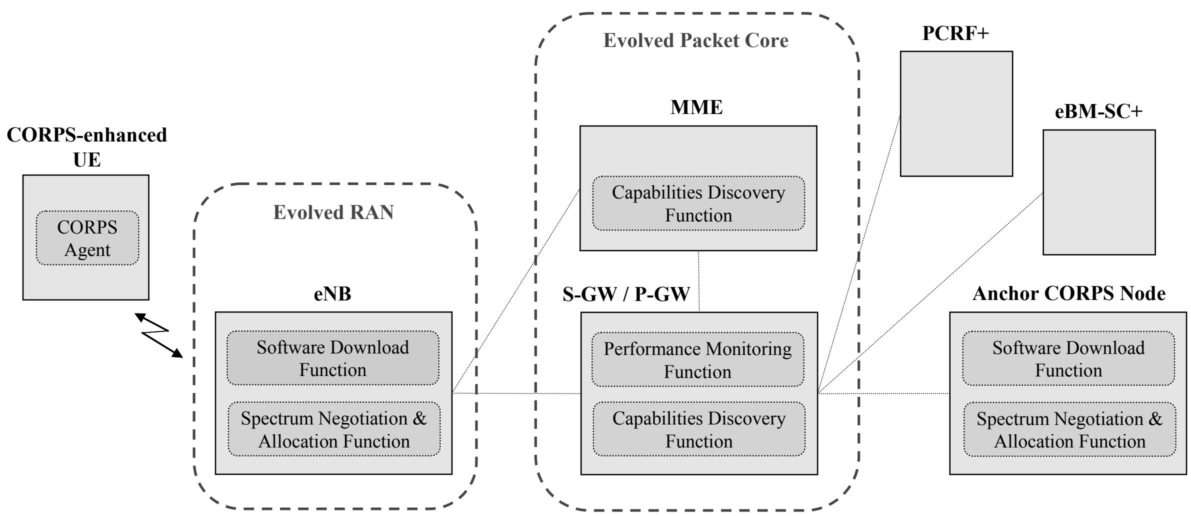

Figure 3. Migration to enhanced 3GPP SAE network for cognitive reconfigurable user equipment

and selection of S-GW and P-GW in upstream signaling. MME functions include management and storage of UE control-plane context, management and allocation of temporary identities, subscription control and admission control during QoS signaling.

The MME is enhanced with the CDF, which participates in capabilities discovery signaling and controls the reconfigurability-related UE control-plane context information and network profile parameters. In addition, the existing MME tracking area update procedure is enhanced with the facility to convey the system capabilities offered by a CORPS-enhanced network.

4) Serving Gateway / PDN Gateway

The S-GW terminates the interface towards the evolved UTRAN and acts as user-plane inter-eNB anchor as well as inter-3GPP mobility anchor. In addition, it is responsible for packet routing and forwarding, uplink/downlink packet marking, buffering of downlink packets for idle-mode UEs, and lawful interception of user-plane traffic.

The P-GW terminates the evolved packet core interface towards the PDN, and acts as user-plane anchor for mobility between 3GPP and non-3GPP systems. P-GW functions include UE IP address allocation, bearer binding, per-user packet filtering, downlink packet marking, gate control, and rate enforcement (e.g., traffic policing/shaping based on the aggregate maximum bit rate per UE). Furthermore, it contains the policy and charging enforcement function, and a charging collection function.

The scenarios when the MME and S-GW are collocated are under discussion in 3GPP. In addition, the cases when the S-GW and P-GW are collocated are for further study. In the following, the term "GW" collectively refers to the S-GW and P-GW, as the present paper does not address roaming scenarios.

The GW is enhanced with the PMF and CDF. The PMF collects performance measures on network-level QoS, which can be sent to the UE PMF. These data can be used by the UE in order to trigger QoS re-negotiation due to inter-system handover, intra-eNB RAT switching, and/or dynamic spectrum access opportunities. In addition, this function tackles the QoS monitoring of user traffic in order to trigger a candidate load balancing procedure or traffic split between access networks. The execution of such decisions is made by existing GW functional entities that operate on network resources. The CDF participates in capabilities discovery signaling and stores the profile parameters of candidate RANs and RATs.

5) Policy and Charging Rule Function

3GPP specifications dictate that the PCRF acts as a policy decision point, with the UE acting as a policy enforcement point. Therefore, there is no need to enhance the PCRF with a new functional entity for policy control. In this article, PCRF features are augmented so that the element is capable to act as UE peer-entity for policy information exchange. The main new capability of the hereafter-called *PCRF+* element is to translate application-specific QoS parameters received from external servers to network-level reconfiguration-policy rules. In addition, it generates new network-level policy rules in response to UE-generated self-governance rules. Policy generation is based on contextual information and reconfiguration events such as availability of new RANs and RATs, UE upgrades, and spectrum negotiation and allocation. Such policy creation by the UE should be synchronized with the PCRF+ in order to avoid policy conflicts. Besides, new UE policies may have to be validated against strategies defined by the visited operator in roaming scenarios.

6) Anchor CORPS Node

The ACN SDF orchestrates the software download process and is responsible for communicating with the UE SDF on post-download tasks such as software validation and activation. On UE request, the SNAF selects the eNB to negotiate for additional spectrum resources, and participates in negotiation with other operators in order to lease spectrum. The eNB selection depends on traffic conditions reported by the GW PMF. In addition, the ACN SNAF allocates spectrum bands to the UE and communicates this information to the UE SNAF along with the granted bandwidth and duration.

7) Evolved Broadcast/Multicast-Service Centre

The evolved BM-SC (eBM-SC) is capable of broadcasting or multicasting information to a large number of devices, and can serve as entry point for MBMS transmissions from content providers [18]. Therefore, the eBM-SC is not enhanced with new functional entities; instead, it is enhanced with the ability of reliable switching from many-unicast to multicast download mode as well as with the capability to broadcast/multicast information on the offered system capabilities through the MBMS air interface (thereby called *eBM-SC+* in Figure 3). The latter functionality necessitates the subscription of the UE to the MBMS service and can be preferred than the other proposed alternatives (i.e., cell/tracking-area update or use of the CPC) when MBMS bearers are available.

V. CREST: Cognitive Protocol Operation and Signaling Exchange

Cognitive and autonomic networks are feedback-based systems that observe the environment, retrieve contextual information, plan and decide their next steps, and act on system resources. This procedure is repeated as long as the overall operation can be improved compared to the previous state [3-5]. The CREST protocol orientates around a cognition loop (Figure 4a) and realizes capabilities discovery, radio-resource negotiation, and spectrum allocation signaling interactions between the cognitive reconfigurable UE and the enhanced 3GPP SAE network. The objective is to improve the QoS of existing connections through RAT-switching and dynamic spectrum access. Figure 4b presents a strategy for CREST operation at the UE, and Figure 5 charts the detailed message sequence in the context of the CORPS-enhanced 3GPP SAE architecture.

The following assumptions are in place. The UE is attached to the network and remains in active-mode for exchanging real-time traffic; the UE has already established a dedicated guaranteed bit-rate (GBR) bearer allowing always-on IP connectivity; the user wishes to maximize the QoS of the real-time service whenever more network resources are available. To this purpose, during the lifetime of the bearer, the UE tries to search for the always-best combination of RAN/RAT and spectrum band in order to upscale the GBR and/or the maximum bit rate (MBR) that characterize the dedicated bearer. The UE is aware of the MME and GW addresses and stores the tracking area identifier (TAI) that denotes the tracking area it belongs [18].

A. Strategy for QoS Improvement

Figure 4b proposes the hereafter called *Lockstep Discovery and Negotiation with Expedited Allocation (LDN-EA)* strategy, which aims to improve the quality of service of the established dedicated bearer. The strategy refers to the second stage of the cognition loop (Figure 4a). The UE attempts to discover the capabilities of candidate RANs and associated RATs in conjunction with negotiation of additional spectrum resources per candidate *<RAN,RAT>* pair and in-advance allocation for the selected eNB and RAT. The term "lockstep" refers to the cascade of discovery and negotiation operations per RAN; the UE discovers the capabilities of each candidate RAN and associated RATs, followed by radio resource negotiation involving the specific *<RAN,RAT>* pair. Such lockstep discovery and negotiation operation minimizes the delay and communication overhead related to the lookup and transmission of profile information from the network to the UE. Moreover, the algorithm ensures that the UE selects a better configuration in an opportunistic fashion. Specifically, the UE allocates the spectrum resources as soon as it discovers the first *<RAN,RAT,spectrumBand>* combination that improves the existing QoS (based on the maximum GBR/MBR criterion). Another advantage of such fast strategy is that it minimizes the decision-failure probability when time-critical decisions must be made (as will be shown numerically in section VI). For this purpose, a negotiation interval is calculated based on system parameters such as the tolerated outage time for the specific *<cell,RAT>*. This timer can be dynamically adapted according to up-to-date parameters such as UE velocity and network conditions (e.g., signal strength, interference level, and critical link-event notifications). The formula for the calculation of the negotiation timer is beyond the scope of this article.

An alternative to the LDN-EA strategy is to collect the capabilities of RANs and RATs in a batch mode, followed by selective radio resource negotiation with the most appropriate RANs/RATs. The UE would then collect a list of improved QoS options by negotiating with a small set of RAN/RAT explorations in order to select the optimal spectrum-access configuration option.

B. Signaling Operation

CREST signaling operates around the proposed cognition loop of Figure 4a as follows.

1) Monitoring/Triggering Stage

During the first stage of the cognition loop, the UE SNAF monitors the CPC (*monitoring case*). As soon as an advertising eNB SNAF transmits an updated directory of the available radio access networks, technologies, and spectrum bands in the area the user roams, the UE SNAF retrieves the directory information and delivers this data to the SGF (steps 1-2). In parallel, the UE CDF may discover the offered reconfiguration option-set (i.e., the three system capabilities described in section III.A) through the MBMS or periodic cell/tracking-area update procedures (*triggering case*). Local link-layer QoS degradation interrupts and application-originated events can be additional triggers.

Upon the above monitoring and/or triggering events, the UE SGF asks the SCRF to provide the status of the currently used RATs as well as of other RATs that are resident in the UE. The SCRF evaluates the available RAT protocol stacks (bandwidth limitations, power requirements, resident operating system, supported protocols) and reports this introspection data to the SGF (steps 3-5).

2) Negotiation, Analysis, and Decision Stage

According to the LDN-EA strategy, steps 6-19 in Figure 5 can take place for more than one candidate RAN dependent on information received from the monitoring/triggering stage.

The UE SGF asks the CDF to discover the detailed capabilities of the network elements along the path to external data networks (step 6). The exact knowledge of capabilities of interior network elements (e.g., packet forwarding treatment) is a crucial paragon when the UE makes a decision either to select another RAN/RAT or to jump to an unoccupied frequency band in order to increase or maintain the received quality of service. The UE CDF contacts the GW CDF using the international mobile subscriber identity (IMSI) as UE identifier (*Capabilities Discovery Request* message at step 7). This message also carries the UE location (i.e., the TAI), the identifiers of the candidate RAN and associated RATs, and the identity of the external network to which the UE is connected (e.g., the network identifier of the

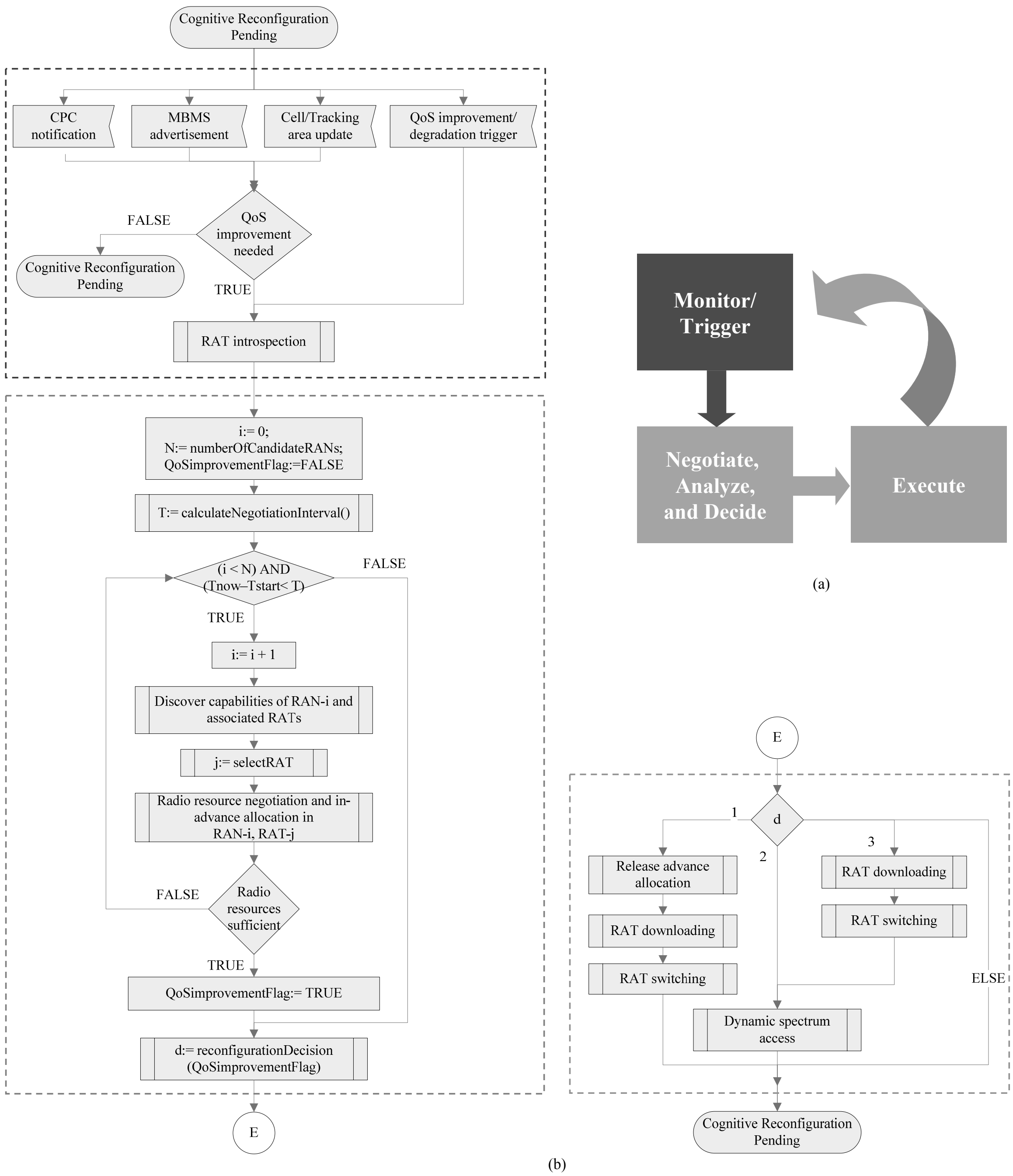

Figure 4. (a) Proposed cognition loop, (b) CREST protocol operation at the user equipment according to the LDN-EA strategy

Figure 5. CREST signaling exchange in the enhanced 3GPP SAE network

access point name (APN)). The GW uses the TAI to find the associated MME (step 8). The requirement here is that, when a RAT is deployed, the GW is updated with the RAN/RAT capabilities (e.g., spectrum bands of the RAT, power levels, maximum sustained traffic, and GBR/MBR per dedicated bearer for each <*RAN,RAT,APN*> triplet). Step 8 involves the GW CDF retrieving the capabilities of the candidate RAN along with the list of RATs capabilities. The *Capabilities Discovery Report* message is sent to the UE CDF, which forwards it to the UE SGF (step 9-10).

When the network capabilities have been discovered, the UE SGF juxtaposes the capabilities of the discovered RATs with the current and resident RATs capabilities, and evaluates the list of GBR/MBR availed to the bearer per RAT. Based on this comparison and evaluation, a decision is made on the best RAT to fulfill the QoS requirements (step 11).

Next, the UE SGF triggers the SNAF to negotiate the allocation of additional radio resources (step 12), based on information received via the CPC (i.e., candidate frequency bands). Whereas the available RANs and RATs change in a rather mid- to long-term fashion (in the order of minutes, hours, or longer), the spectrum bands are freed and occupied rapidly. Therefore, the target eNB has to acquire the necessary excess spectrum resources (if not all requested resources are currently available), and inform the UE when these resources are allocated. The *Radio Resource Negotiation Request* message is sent from the UE SNAF to the ACN SNAF, which selects and queries an appropriate eNB (from the selected RAN; with the required RAT installed), according to performance and availability criteria (steps 13-15). Such information can be delivered to the ACN from the GW PMF. The specific algorithm for eNB selection is beyond the scope of this article and is briefly discussed in the sequel.

CREST is designed to avoid the case of multiple UEs discovering and negotiating with the same <*RAN,RAT*> set, which would potentially yield an early allocation of the foreside spectrum bands. The first solution is to have each UE randomly selecting the RAN to start the capabilities discovery procedure (i.e., at step 6). Such random-choice algorithm can be based on the IMSI, which is a globally unique identifier, thus yielding different ordered lists. A second level of searching order can be achieved at step 9; the GW can dictate a specific RAT-order by delivering different lists of candidate RATs based on priorities. These priorities can be dependent on the requester UE (e.g., subscription-based by inspecting the IMSI value). The third solution for evenly distributed searching orders can be enforced at step 14, when the ACN selects the target eNB for spectrum allocation. Operator-oriented policies can be employed here. For example, the ACN can consult the GW PMF in order to achieve a load balancing policy, wherein the UEs are directed to the least-loaded eNB and/or the least-loaded spectrum bands from the available pool. The ACN can make such decisions based on eNB load reports and interference measurements. It is worth noting that spectrum-band searching order does not affect the QoS of existing UE bearers due to the coordinated centralized nature of spectrum allocation.

The eNB SNAF attempts to acquire spectrum from neighboring base stations in order to increase the capacity offered to its associated users. Steps 14-17 are repeated until an appropriate eNB that can grant the excess bandwidth for the minimum requested duration is selected. When an eNB manages to borrow some spectral resources, the result is reported to the ACN, which in turn delivers a *Radio Resource Negotiation Report* message to the UE (steps 16-19).

The negotiation and analysis actions have been completed, and the UE SGF should decide the reconfiguration strategy in order to improve the QoS requirements of the bearer (step 20). The UE decides whether to (1) switch to another radio-access technology with or without handing over to another base station (i.e., vertical and horizontal handoff), (2) hop to the unoccupied spectrum band (i.e., spectrum handoff), or (3) make a combined selection. Inputs to this decision algorithm are the GBR/MBR of the bearer connection (from the UE to the external network via the selected RAN and RAT), the capabilities of the selected RAN and RAT, and the outcome of the radio-resource negotiation procedure (spectrum band, granted bandwidth, and granted duration fields).

3) Execution Stage

The execution steps are rather straightforward. In case the decision d is "1" or "3" (see Figure 4b), the UE should download any missing radio-software modules of the selected RATs. Such action involves the SDF at the UE and the ACN. For $d = 1$, the advance allocation at the selected eNB is released through either soft state or an explicit release message. For $d = 2$, the UE SNAF accesses the free spectrum after getting clearance from the SGF. Alternatively, the UE SGF commands the SCRF to switch to the selected RAT.

VI. CREST Analysis and Evaluation

This section evaluates the performance of the proposed CREST signaling. Analytical expressions are systematically computed and numerical results show the efficiency of CREST in terms of total signaling delay and decision-failure probability.

A. Analytical Exressions

Table 2 summarizes the parameters and variables used in the analysis and Figure 6 illustrates the network topology. In Figure 6, the bold line indicates the signaling path. The cost of each signaling message is proportional to a) the network distance (in terms of IP hops) between the communication endpoints and b) an average per-hop transmission and link cost (in terms of delay). The formulas consider the signaling messages between network elements; the cost of messages exchanged between functional entities that are mapped to the same network element is either computed as part of the local processing cost or assumed zero. Given the establishment of pre-reserved dedicated signaling channels, the queuing delay of signaling messages is assumed zero.

1) Partial and Cumulative Signaling Delays

The delay of the monitoring/triggering stage D_m is given by

$$D_m = \frac{s}{B_s} + t_{wl} + C_{p,2-5}, \qquad (1)$$

Table 2. Parameters and variables

$d_{S1\text{-}MME}$	average length of the S1-MME reference point (eNB-MME distance)
d_{S11}	average length of the S11 reference point (MME-GW distance)
d_{SGi}	average distance between the GW and the ACN (through the SGi reference point)
t_{wl}	wireless link delay
t_w	wireline link delay
s	average message size
B_s	bandwidth of the signaling channel
C_p	processing cost
N	number of candidate RANs
k_i	number of queried eNBs in currently-polled RAN i
f_c	frequency of cognition events (e.g., average number of times the network advertises CPC information per unit of time)
f_d	frequency of launching the discovery procedure (i.e., average number of times the UE triggers the LDN-EA algorithm per unit of time)
P_n	probability of launching negotiation signaling for the selected RAT
T_r	RAT/spectrum-band residence time with mean $E[T_r]$ and density function f_r

where the first term corresponds to the transmission of the *CPC Directory Update* message, s is the average message size transmitted over a signaling channel with bandwidth B_s, t_{wl} is the associated wireless link delay, and $C_{p,2\text{-}5}$ expresses the local message exchange and processing cost at the UE for protocol stack introspection (steps 2-5).

The second stage consists of the discovery and negotiation/allocation procedures. The discovery procedure consists of the *Capabilities Discovery Request/Report* messages, as well as a profile retrieval operation at the GW (steps 6-10). Therefore, the overall delay D_d of the discovery stage is given by

$$D_d = 2(d_{S1-MME} + d_{S11})(\frac{s}{B_s} + t_w) + 2(\frac{s}{B_s} + t_{wl}) + C_{p,8}, \tag{2}$$

where t_w is the wireline link delay and $C_{p,8}$ represents the profile retrieval cost at step 8.

The negotiation procedure with each candidate RAN i involves querying a maximum number of k_i eNBs. Therefore, the signaling cost D_n for steps 11-19 is expressed as follows:

$$D_n = 2(d_{S1-MME} + d_{S11} + d_{SGi})(1 + k_i)(\frac{s}{B_s} + t_w) + 2(\frac{s}{B_s} + t_{wl}) + C_{p,11} + k_i(C_{p,14} + C_{p,16}). \tag{3}$$

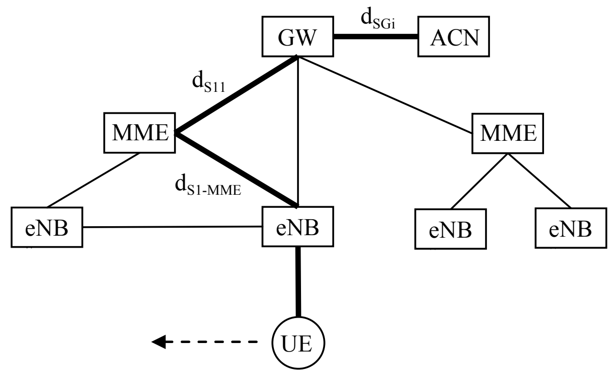

Figure 6. Network topology used for analysis

The first two components correspond to the transmission and link delays of the *Radio Resource Negotiation Request/Report* and *Spectrum Resource Query/Result* messages. $C_{p,11}$ is the RAT selection delay, whereas $C_{p,14}$ and $C_{p,16}$ express the processing costs for eNB selection and spectrum acquisition/rearrangement at steps 14 and 16, respectively.

In the worst case, the LDN-EA strategy involves discovering and negotiating with all k_i eNBs for each of the N available radio-access networks (i.e., operators), $i=1,\ldots,N$. Therefore, the worst-case deterministic signaling cost of the monitoring, discovery and negotiation/advance-allocation procedures is given by

$$D_{tot} = D_m + \sum_{i=1}^{N}(D_d + D_n). \tag{4}$$

The ensemble average of the total signaling cost can be expressed as follows:

$$E[D_{tot}] = f_c \cdot D_m + f_d \cdot \sum_{i=1}^{N}(D_d + P_n D_n), \tag{5}$$

where f_c is the cognition frequency (e.g., the rate of CPC advertisements) and f_d is the average number of times the UE triggers the second stage of the cognition loop per unit of time. P_n is the probability of starting the negotiation phase at step 12 upon successful completion of the discovery steps.

2) Decision Failure Probability

We define the decision failure probability as the likelihood of unsuccessful completion of CREST signaling before the UE leaves the serving RAT or evacuates the spectrum channel. The analysis that follows is based on the definition of blocking probability in [19].

Let D be a random variable denoting the cumulative signaling delay with mean $E[D]$ and distribution function F_D. Let T_r be the RAT/spectrum-band residence time with mean $E[T_r]$ and density function f_r. Following the analysis in [19], we assume that D and T_r are independent exponentially distributed random variables. The exponential distribution is an acceptable assumption when evaluating signaling costs, for it eases the derivation of analytical expressions without compromising the accuracy of the analysis [19,20]. CREST signaling fails to complete successfully (i.e., a decision failure occurs) when $D > T_r$:

$$P_f = \Pr(D > T_r) = \int_0^{\infty} \Pr(D > u) f_r(u) du$$

$$= \int_0^{\infty} [1 - F_D(u)] f_r(u) du = \frac{E[D]}{E[D] + E[T_r]}. \quad (6)$$

B. Performance Evaluation

Figure 7 illustrates the worst-case total deterministic signaling delay for varying negotiation set. The figure considers 10ms wireless link delay and 2ms wireline link delay. The end-to-edge distance from the eNB to the ACN is 7 hops ($d_{S1\text{-}MME} = 2$, $d_{S11} = 4$, $d_{SGi} = 1$). We assume a per-hop transmission delay of 3ms, which corresponds to an s = 144-byte control packet carried over a B_s = 384kbps signaling channel. Other parameter values used to compute the cumulative delay are defined as follows: $C_{p,2\text{-}5} = C_{p,8}$ = 1ms (delays for profile parameter retrieval), $C_{p,11} = C_{p,14}$ = 0.05ms, $C_{p,16}$ = 1ms. As expected, the total signaling delay increases with the number of candidate RANs and base stations. Nevertheless, the worst-case CREST signaling delay is sustainable; in fact, it ranges between a few hundreds milliseconds up to no more than 3 seconds (for a negotiation set of 30 eNBs in total).

Figure 8 shows the partial and cumulative worst-case signaling delays as a function of the wireless link delay. The figure assumes $N = 3$ RANs with k_i = 3, 5, 4 eNBs, respectively. The partial and total delays linearly increase with the wireless link delay, where the negotiation component has the major contribution to the total delay. It is well known that the end-to-end delay of a typical inter-RNC intra-SGSN soft handover is in the order of seconds (in fact, it ranges from around 2 to 16 seconds, depending on the multi-RAN network architecture and the traffic mix [21]). Hence, drawing an analogy between the SGSN and the MME, CREST meets the soft-handover requirement, as the overall signaling delay falls within these thresholds (even when negotiating with a dozen eNBs).

Figure 9 plots the total signaling delay versus the bandwidth of the signaling channel, for various ($d_{S1\text{-}MME}$, d_{S11}, d_{SGi}) triplets and (N, Σk_i) values, with s = 144 bytes. Clearly, the signaling delay reduces with the channel bandwidth. A total signaling delay of 1 second is obtained for (2,4,1) distance values with two operators offering six eNBs in total and B_s = 256kbps. A value of 500ms can be obtained with, for example, two operators, four eNBs, and B_s = 384kbps. Latencies lower than 200ms are feasible for the (1,2,1) and (1,1,1) distance series, with one operator and two or three eNBs. Therefore, CREST is compliant with spectrum-agility, when band availability quickly varies over time.

Figure 10 shows that CREST exhibits a much lower decision failure probability when the average residence time increases. This is due to the ability of

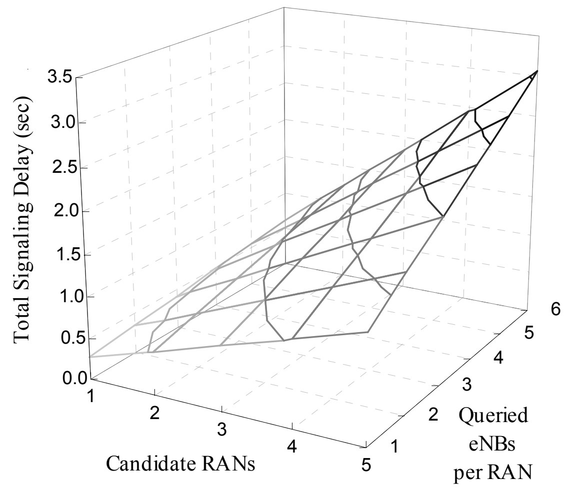

Figure 7. Worst-case total signaling delay for varying negotiation set

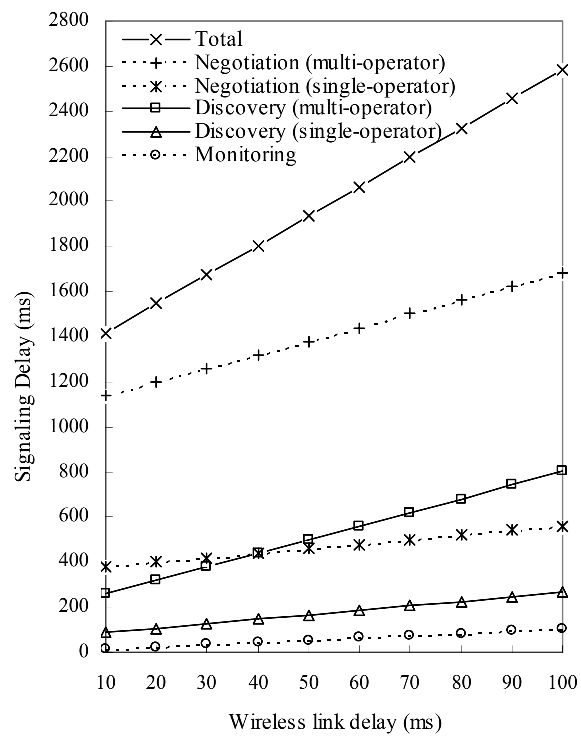

Figure 8. Worst-case partial and total signaling delays versus wireless link delay ($N = 3$, $\Sigma k_i = 12$)

CREST to make a timely decision while the UE continues to use the present RAT or occupies the previously allocated spectrum band. An almost zero decision-failure probability can be achieved when the mean signaling delay is below the maximum tolerable latency for seamless handovers (i.e., 200ms). Therefore, CREST can facilitate seamless service continuity due to faster signaling exchanges and swift operation of UEs.

VII. Related Protocols

The signaling protocol in PROMETHEUS [22] is considered the closest to this work. However, its functionality is very limited compared to CREST; mainly, it supports wireless network identification and interference avoidance. IP-based core networks are assumed, but no details with respect to architectural elements and signaling exchange are given.

DSAP [23] is a simple DHCP-like request/response protocol that uses a small set of messages between the client device and the DSAP server for coordinated dynamic spectrum access. DSAP targets geographically limited areas (such as indoor environments) and addresses channel switching at small time-scales in WLAN-only networks. RAN/RAT discovery and selection are not supported.

In both [22] and [23], detailed signaling and parameters for capabilities discovery and radio resource negotiation are not specified, and on-line RAT downloading and switching are not supported by the protocols. Furthermore, 3GPP systems and signaling between specific network elements are not considered.

DIMSUMNet [24] provides an IP-based architecture for regional spectrum brokering and SPEL, a protocol for communication between the spectrum broker and the RAN manager. In the first mode of operation, negotiation of spectrum leases between base stations and the spectrum broker occur during base-station bootstrapping, not dynamically when the UE is in active state. The second mode of operation allows on-demand traffic channel request by the UE. Nevertheless, spectrum acquisition is foreseen from the same serving base station, which may not always be feasible and optimal (real-time base station selection is not foreseen). In addition, requests from many UEs are aggregated by the base station and forwarded to the spectrum broker (i.e., requests are not served on a per-UE basis). Finally, detailed signaling flows are not given, and the architecture and protocol do not examine the case of UMTS networks.

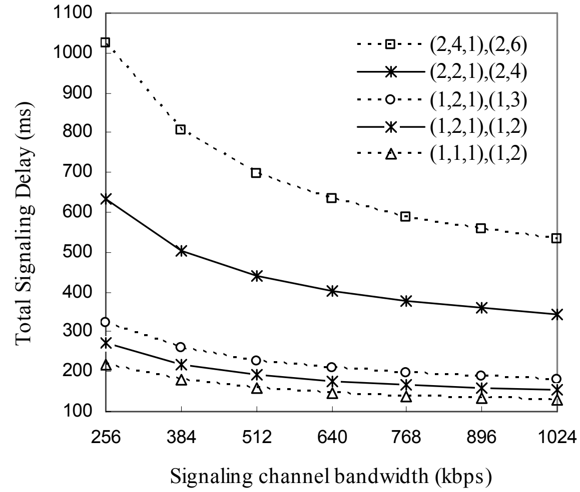

Figure 9. Worst-case total signaling delay versus signaling channel bandwidth, for various network distances and negotiation sets

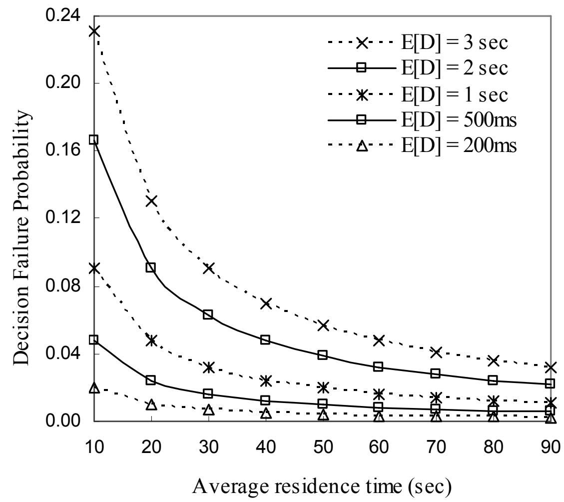

Figure 10. Decision failure probability versus average RAT/spectrum-band residence time

VIII. Conclusions

This article has proposed a new architecture and a novel signaling protocol for smooth migration to cognitive reconfigurable post-3G mobile systems. Whereas the research community focuses on implementation aspects of software radio and algorithms for spectrum sharing [25], there has been, to the best of our knowledge, no attempt so far to provide unified architectural solutions with comprehensive signaling exchange over real-world systems such as the 3GPP SAE network.

The CORPS architecture embodies modular software and cognitive radio features whilst introducing autonomic capabilities for the user equipment. CORPS is modeled according to foundations of accredited practices in the industry, such as the 3GPP IRP and OMG MDA approaches. The proposed CREST protocol aims to fill the gap in the literature in the area of signaling in cognitive reconfigurable 3GPP networks. Finally, the article has proposed LDN-EA, a fast strategy for capabilities discovery, radio resource negotiation, and in-advance spectrum allocation via CREST messages. It is worth noting, however, that CREST signaling messages are independent of the adopted strategy, and alternatives to LDN-EA have been discussed. Analytical expressions have been introduced with numerical results showing the efficiency of the proposed signaling.

Next steps include evaluation of the alternatives in CREST protocol operation (discussed in section V). Extensions for intra-domain connection of eNB nodes to multiple core-network nodes (via the S1-flex interface), network sharing (shared eNB or core network nodes), inter-operator spectrum sharing, and roaming scenarios will also be studied. Future work includes investigation on the available protocol pool and identification of possibility to carry some CREST messages over extensions of existing protocols. IETF NSLP [26] is a candidate protocol for QoS negotiation in 3GPP SAE networks.

Appendix. List of Abbreviations

ACN	Anchor COPRS Node
CDF	Capabilities Discovery Function
CORPS	COgnitive Reconfigurable Post-3G System
CPC	Cognitive Pilot Channel
CREST	Cognitive REconfiguration Signaling proTocol
eNB	evolved Node B
GBR	Guaranteed Bit Rate
GW	GateWay
IMSI	International Mobile Subscriber Identity
LDN-EA	Lockstep Discovery and Negotiation with Expedited Allocation
MBR	Maximum Bit Rate
MME	Mobility Management Entity
PMF	Performance Monitoring Function
RAT	Radio Access Technology
SAE	System Architecture Evolution
SCRF	Self-Configuration & Resource management Function
SDF	Software Download Function
SGF	Self-Governance Function
SNAF	Spectrum Negotiation & Allocation Function
TAI	Tracking Area Identifier
UE	User Equipment

Acknowledgment

The first author would like to acknowledge the Alexander S. Onassis Public Benefit Foundation for a doctoral fellowship.

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