Architectures and Signaling Protocols for Cognitive Reconfigurable Mobile Networks

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Abstract. Cognitive wireless networks and reconfigurability emerge as the paradigms that will transform the mobile communications landscape in the next decades. One of the prerequisites for the adoption of cognitive radio and online switching of radio access technologies (RATs) in infrastructure-based mobile networks is the signaling protocol. This thesis introduces a new architecture and signaling solution that unify the dynamic selection of radio access technologies and spectrum bands. RAT/spectrum mobility is achieved through a fast strategy for discovery of RAT capabilities, radio resource negotiation, and in-advance coordinated spectrum allocation. First, the architecture and protocol design in terms of functional entities, signaling exchange, and deployment over the most important and challenging next-generation network infrastructure, that is, 3GPP System Architecture Evolution (SAE), is described. Next, the thesis provides analytical expressions for the signaling delay and load, as well as for the signaling-failure probability. Design improvements are analyzed and evaluated, with numerical results showing the efficiency of the protocol and its variants. Furthermore, comparison with related works highlights the suitability of the proposed signaling for RAT/spectrum mobility in both large metropolitan realms and geographically limited networks. Finally, the thesis proposes and evaluates a reconfiguration support architecture and protocol that extend the ETSI next-generation network (NGN) framework. The protocol introduces novel signaling solutions for registration of reconfigurable devices to the network, negotiation of operational mode, and administration of the radio-software download process, with the architecture being modular and inline with the subsystem-oriented rationale of NGN.

Keywords: cognitive networks, mobile communication systems, protocol design and analysis, reconfiguration, wireless communication.

1 Dissertation Summary

1.1 Motivation, Challenges, and Contributions

Cognitive radio and reconfigurability emerge as the most challenging paradigms that

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will radically transform the mobile communications era in the next decade [1],[2]. Roadmaps show that the availability of a wide range of radio-access technologies (RATs) will be a reality in the short-term, with LTE/LTE-Advanced, HSPA evolution, WiMAX, and Wi-Fi being the key players. Cognitive radio is an evolution of the Software-Defined Radio (SDR) concept [3], defined as a radio that is aware of the surrounding environment, learns from such environmental information, and adapts its operating parameters (e.g., carrier frequency, transmit power, modulation strategy) in real time, aiming at the efficient utilization of radio spectrum [1].

The present thesis addresses two main challenges in next-generation cognitive wireless networks. The first research question is how to introduce efficient architecture and signaling solutions for dynamic selection of radio access technologies and spectrum bands. In this context, the thesis aims at *RAT/spectrum mobility*, i.e., a combination of vertical handover (VHO) and dynamic spectrum access (DSA). The second research challenge is how to enhance next-generation networks with *mode negotiation* and *radio-software download capabilities* for reconfiguration of mobile devices.

The thesis identifies the following gaps in the literature [4],[5],[6]. Firstly, dynamic spectrum access studies focus on spectrum sensing and sharing algorithms, with existing signaling protocols for dynamic spectrum allocation exhibiting significant limitations. Second, RAT selection has been examined separately from spectrum band selection, and thus protocols for combined RAT/spectrum mobility have not yet been proposed. Third, RAT selection has been studied from the decision-making (i.e., algorithmic) viewpoint; protocols for discovery of RAT capabilities and RAT-software download have been less covered. Finally, radio-software download studies focus on reliable mass upgrades; pre-download tasks, such as mode negotiation, have not yet been introduced.

In this context, the thesis consists of two contributions. The first contribution covers the design and performance analysis of architectures and protocols for RAT/spectrum mobility [7],[8]. We propose *CREST (Cognitive REconfiguration Signaling proTocol)*, a new signaling protocol for quality of service (QoS) improvement via RAT switching and/or coordinated DSA. In addition, we propose a new strategy that unifies the discovery of capabilities of candidate RATs with spectrum negotiation and in-advance allocation for the selected RAT. Besides, the thesis proposes *CORPS (COgnitive Reconfigurable Post-3G System)*, a new architecture that supports CREST protocol operation via modular cognitive/software radio features, and can be deployed over the most important and challenging mobile network architecture, that is 3GPP SAE (System Architecture Evolution) [9].

The second contribution lies in the introduction of reconfiguration capabilities in next-generation networks as standardized in the ETSI NGN (next-generation network) framework [10],[11]. Specifically, we propose *RRP (Radio Reconfiguration Protocol)*, a new signaling protocol for registration of reconfigurable devices to the network, negotiation of operational mode, and administration of the radio-software download process. Besides, we propose *RSS (Reconfiguration Support Subsystem)*, a new modular architecture that bases on the philosophy and functional decomposition of the IP Multimedia Subsystem (IMS) and extends the subsystem-oriented rationale of ETSI NGN.

1.2 Related Work

Although many algorithms for dynamic spectrum access have been proposed in the literature [2],[12], the area of signaling protocols for cognitive wireless networks has been less addressed. Besides, to the author's knowledge, protocols for combined RAT/spectrum mobility have not yet been proposed. Brik et al. [13] describe DSAP, a simple DHCP-like request/response protocol that adopts coordinated DSA and focuses on channel switching at short time scales. The main limitation of DSAP is that it covers geographically limited networks (e.g., private indoor environments), and has been designed for WLAN-only networks. RAN/RAT discovery is not supported, and thus RAT-software downloading and switching are not foreseen. Buddhikot et al. [14] propose DIMSUMNet, an architecture for regional spectrum brokering, and SPEL, a protocol between the radio access network (RAN) manager and the so-called spectrum broker. DIMSUMNet exhibits two drawbacks: Firstly, spectrum acquisition is foreseen from the same serving base station, which may not always be feasible or optimal; consequently, real-time base station selection is not supported. Second, requests from many user equipments (UEs) are aggregated by the base station and forwarded to the spectrum broker; that is, requests are not served on a per-UE basis. PROMETHEUS, as proposed in [15], has limited functionality compared to CREST. Wireless network identification is supported; nevertheless, discovery of detailed RAT capabilities is not foreseen. Besides, whereas PROMETHEUS caters for interference avoidance, it lacks spectrum-resource negotiation capabilities. In addition, both PROMETHEUS and DIMSUMNet bear the following limitations: a) RAT downloading and switching are not supported, b) they assume a high-level architecture (based on a generic All-IP core network); they do not address the most important and challenging next-generation architecture, i.e., 3GPP SAE, and do not give details on the required network elements and signaling parameters. The authors in [16] propose a credit-token-based rental protocol for dynamic spectrum sharing. Their scope is limited compared to CREST; they focus on inter-cell spectrum auctioning and signaling between the primary and secondary base station. This protocol can act complementary to CREST, as explained in [8].

Although the problem of RAT selection has been studied in the literature, the case of signaling protocols has been less covered. Moreover, VHO (i.e., RAT selection for active state UEs) has been examined separately from the DSA challenge. In [17], the authors propose connection establishment for inter-RAT UTRAN-to-GERAN handoff. However, they assume a common radio-resource management server in the network, a concept that has not progressed within 3GPP. On the contrary, CREST proposes the migration to self-governance, with the RAT-selection decision made locally at the UE. Recent 3GPP SAE specifications provide signaling solutions for context transfer and bearer switching [9]; in the case of a combined horizontal and vertical handoff, such excess signaling can occur in parallel to CREST execution-stage signaling. Other studies focus on RAT decision-making algorithms without addressing the signaling aspects. For example, [18] proposes RAT selection policies based on Markov chains. In [19], the authors formulate VHO decision-making based on a Markov decision process that takes into account the connection-switching signaling cost, and provide a comprehensive overview of other VHO decision algorithms.

Work related to RSS/RRP focuses on advertising the availability of software upgrades to a group of mobile terminals, with emphasis on transmission and processing costs [20], as well as on the performance of reliable mass upgrades in 3G networks [21]. The studies in [22] and [23] propose scalability solutions for mass upgrades via switching from “many-unicast” to multicast transmission, whereas [24] addresses decision-making issues for transport-layer optimization during software download. The authors in [25] study parameters affecting the radio-software download latency in GSM/GPRS and UMTS networks, whereas [26] proposes the reconfiguration of mobility management protocols in the core network and analyzes the incurred signaling cost. Finally, although [27] covers content download (i.e., non-operational software), it proposes interesting session management mechanisms for seamless download continuity during horizontal or vertical handoff.

2 Results and Discussion

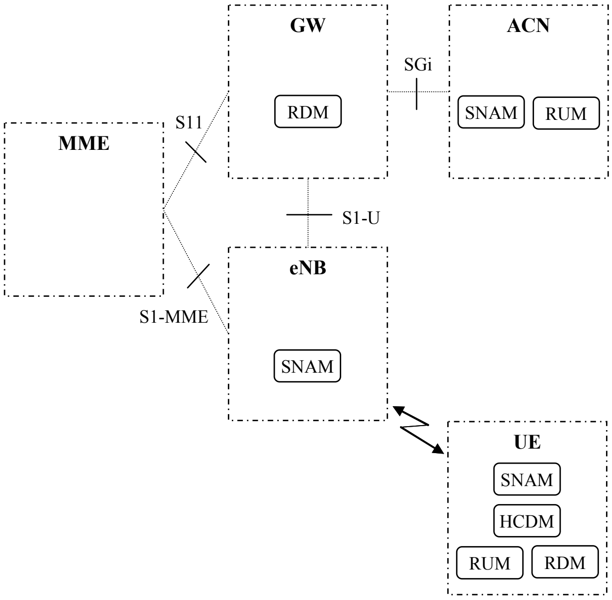
2.1 CORPS-enhanced 3GPP SAE Architecture

Fig. 1 illustrates the proposed CORPS functional entities deployed over 3GPP SAE network elements. We have selected 3GPP SAE [9] as the target network architecture, for it comprises the most important and challenging next-generation architecture for mobile communications. One of the main drawbacks of SAE is that it assumes multi-mode devices with pre-installed RATs. Besides, present 3GPP specifications are biased in favor of intersystem mobility, with dynamic spectrum access not foreseen for the forthcoming releases. However, 3GPP has recently launched activities towards multi-standard radio, which aims at RF parameter harmonization and is considered as the first step towards SDR and cognitive radio. The CREST protocol aims to fill those gaps and provide a signaling solution for the deployment of cognitive/software radio facilities in future 3GPP specifications.

2.2 CREST Protocol Operation and LDN-EA Strategy

CREST aims to improve the QoS of user sessions through RAT-switching and dynamic spectrum access. We propose such functionality through the unification of RAN/RAT capabilities discovery, radio-resource negotiation, and spectrum allocation operations. CREST is invoked by those users who wish to maximize the QoS of real-time services whenever more network resources are available. Either upon session establishment or during the lifetime of an existing session, the UE tries to search for the always-best combination of RAN/RAT and spectrum band, in order to upscale QoS attributes (e.g., the guaranteed bit rate (GBR) or the maximum bit rate (MBR)) of the dedicated bearer.

In [7], we proposed the *Lockstep Discovery and Negotiation with Expedited Allocation (LDN-EA)* algorithm. According to LDN-EA, 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 spectrum allocation for the selected evolved Node B (eNB) and RAT. The



Legend

ACN	Anchor CREST Node	RDM	RAN/RAT Discovery Module
eNB	evolved Node B	RUM	RAT Upgrade Module
GW	Gateway	SNAM	Spectrum Negotiation and Allocation Module
HCDM	Handoff Classification and Decision Module	UE	User Equipment
MME	Mobility Management Entity		

Fig. 1 Deployment of CORPS functional entities over a 3GPP SAE network.

term “lockstep” refers to the cascade of discovery and negotiation stages per candidate RAN. Allocations are “expedited” since the strategy is to allocate spectrum in advance when the negotiation stage allows to do so for the currently examined <RAN, RAT> pair.

The protocol operation consists of four stages:

- Stage 1: *Cognition* (through external triggering).
- Stage 2: *Discovery* of RAN/RAT capabilities.
- Stage 3: *Negotiation and allocation*.
- Stage 4: *Handoff decision-making and execution*.

During the *cognition stage*, the UE retrieves the directory information via the cognitive pilot channel (CPC) [28]. If QoS improvement is needed, the UE introspects the operating/resident RATs and proceeds to the *discovery and negotiation/allocation stages*. For each candidate RAN, the UE a) discovers the detailed RAN capabilities, as well as the capabilities of deployed RATs, b) selects the most appropriate RAT, and c) negotiates for additional spectrum resources. If the discovered resources are not sufficient, the UE continues by exhausting the list of available RANs. When the requested resources can be committed, the UE enters the *decision-making and* *execution stage*, where different signaling operations occur depending on the handoff decision (VHO, DSA, or joint VHO/DSA).

2.3 CREST Signaling

Fig. 2 charts the proposed signaling exchange between the UE and the network elements of the CORPS-enhanced 3GPP SAE.

During the cognition stage, the UE retrieves the CPC directory information from an advertising eNB (steps 1-2). Next, the introspection procedure returns key information on the operating and resident RATs (steps 3-5). During the second stage (steps 6-8), the UE sends the *Capabilities Discovery Request* message, which carries the following technology-specific identifiers: <*source (International Mobile Subscriber Identifier (IMSI)), location (Tracking Area Identifier (TAI)), candidate RAN identifier, associated RATs identifiers, destination (Access Point Name (APN))*>. The gateway (GW) retrieves and sends the requested profile attributes, including the supported bitrates (GBR/MBR) per RAT.

During the third stage, the UE makes the RAT selection decision locally (step 9), using the information received at step 8. Next, it sends a *Radio Resource Negotiation Request* message to the Anchor CREST Node (ACN), requesting for *excessBandwidth* for a *minDuration*, for the selected RAN and RAT. The ACN selects and queries an available eNB; steps 11-14 are repeated until an eNB replies with the necessary spectrum resources for the requested duration. Step 13 may involve two additional operations: a) the eNB may negotiate spectrum resources from neighboring eNBs, using a mechanism such as the credit-token protocol proposed in [16]; b) the eNB that avails the requested spectrum resources may also negotiate with the GW for the required transport capacity. This way, resources in the core network are also reserved, thus assuring the complete end-to-edge data path. When the negotiation loops are completed, the ACN reports the eNB address and the <*granted bandwidth, spectrum band, granted duration*> triplet to the UE (step 15).

Stage 4 signaling is omitted due to space limitations. Details can be found in [8].

2.4 CORPS/CREST Performance Evaluation

We systematically compute the decision-making signaling delay (stages 1-3), as well as the total signaling delay (due to all four stages of protocol operation). Furthermore, we compute the signaling-failure probability when a UE employs the CREST protocol, and the signaling load at key network elements of the enhanced 3GPP SAE network (Fig. 1). Finally, we compute the signaling delay ratio/reduction for a new version of the protocol (called *CREST-2*) versus baseline CREST. Details on the analytical model can be found in [7] and [8].

The values for the performance evaluation have been used for the analysis of IMT-2000 (i.e., 3G) systems [29] and approximate to future IMT-Advanced (i.e., 4G) recommendations. In [8], we defined the *Session-to-Cognition Ratio (SCR)* as the ratio of the session arrival rate over the cognition-triggering rate. Besides, we have

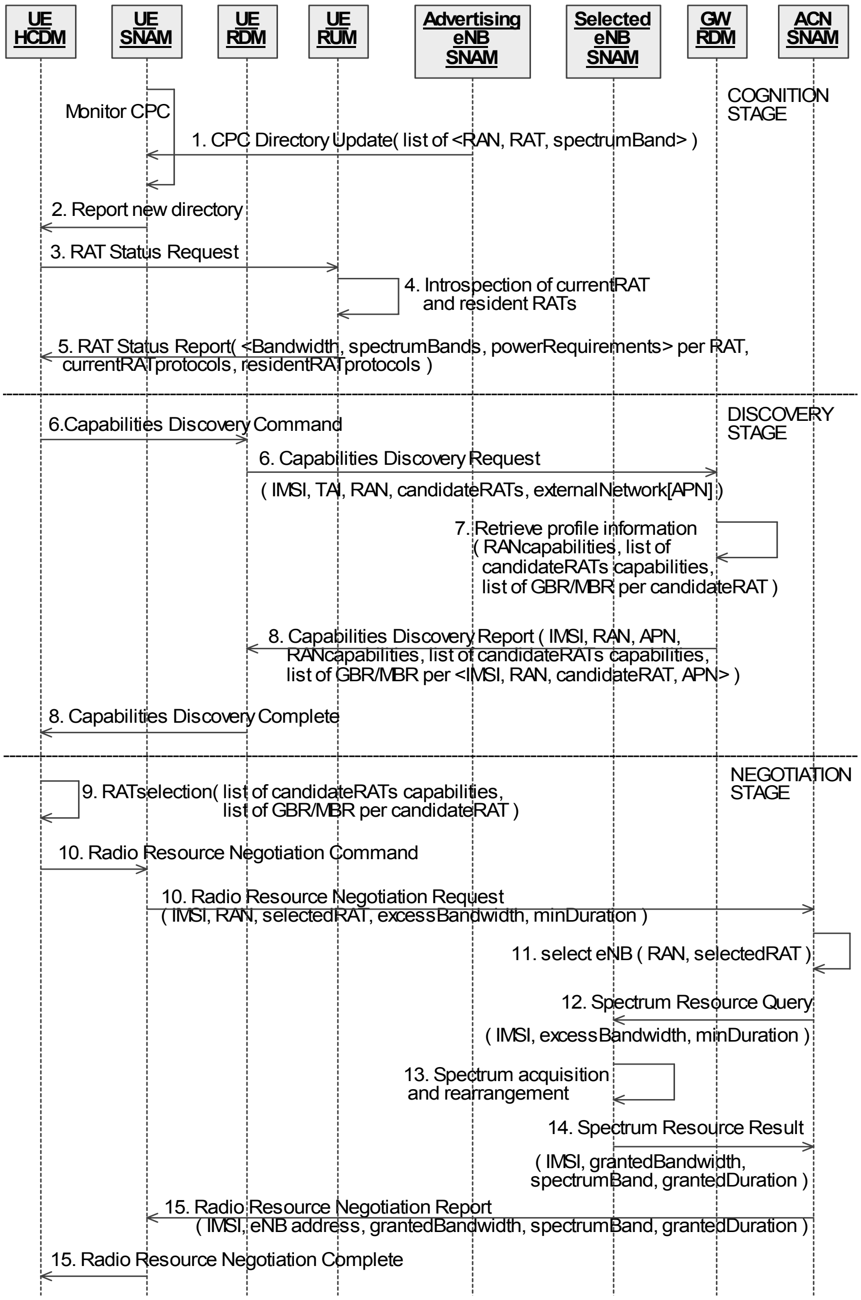


Fig. 2 CREST signaling for stages 1-3 (cognition, discovery of RAN/RAT capabilities, and negotiation/advance-allocation).

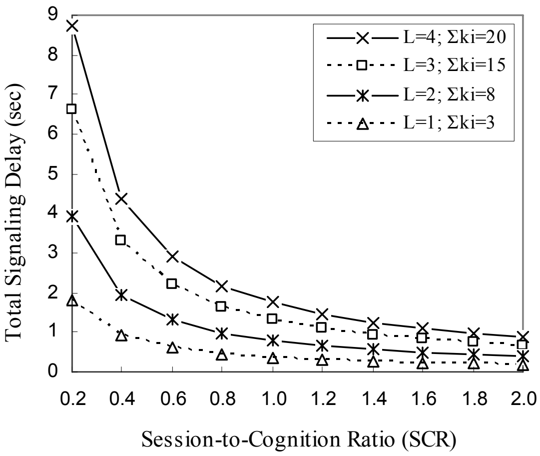


Fig. 3 Average total signaling delay versus SCR for varying negotiation set.

introduced the notion of *Mobility-to-Cognition Ratio (MCR)*, which indicates the ratio of the number of times the UE initiates the capabilities discovery procedure per unit of time to the frequency of cognition events. The notions of SCR and MCR extend the concepts of call-to-mobility ratio [30],[31] and session-to-mobility ratio [32], which have been introduced in location management architectures and strategies.

Fig. 3 illustrates the average total signaling delay as a function of the SCR and for varying negotiation set. L ranges from one to four operators offering from three up to five eNBs each (maximum Σk_i = 20 eNBs). The total signaling delay is higher for low values of SCR. This is because the signaling traffic increases when the average number of cognition opportunities per unit of time dominates over the session rate. Conversely, when the average inter-cognition time is higher than the average inter-session duration (i.e., SCR > 1), the UE launches CREST less often. Then, the signaling traffic is considerably reduced. As expected, the signaling exchange is higher when involving a large number of RANs and candidate eNBs. However, when the mobile terminal can avail a couple of CREST attempts per session (i.e., the SCR is smaller than one but not too small to throttle the UE with cognition triggers), it can be seen that the overall signaling delay is sustainable, provided no more than a dozen eNBs are queried. The total deterministic (i.e., for SCR = 1.0) worst-case latency is sustainable for non-time-critical handovers (less than 2 seconds even for higher values of the wireless link delay).

Fig. 4 shows that CREST exhibits lower signaling-failure probability for higher average RAT/spectrum-band residence times and shape parameters γ. Less than 1% probability of failure can be achieved when the mean signaling delay is below 200ms, which is the maximum tolerable delay for seamless service continuity. Such delay threshold is feasible with CREST-2 in MME-oriented architectures (as proposed in [8]). Therefore, CREST-2 can facilitate seamless service continuity in spectrum-agile environments, due to faster signaling exchanges and swift operation of UEs. Signaling-failure probability decreases with the average residence time due to the

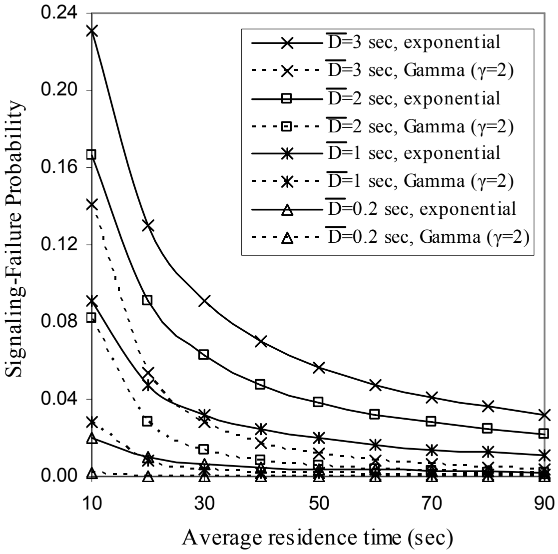


Fig. 4 Signaling-failure probability versus average RAT/spectrum-band residence time, for varying average signaling delay and residence time distributions.

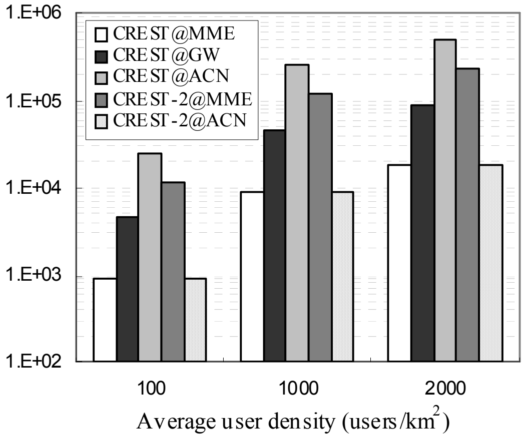


Fig. 5 CREST and CREST-2 signaling loads (in bytes per second) versus average user density.

ability of CREST to make a timely handoff decision while the UE continues to use the present RAT or as long as the lease duration allows the UE to occupy the previously allocated spectrum band.

Fig. 5 illustrates that CREST-2 achieves about 30 times lower ACN signaling load compared to basic CREST, as well as offloading at the GW (which does not participate in any CREST-2 signaling). Such performance gains come at the cost of twelve times higher MME load. Nevertheless, both CREST-2 and CREST signaling loads are sustainable, compared to the figures reported in [33] for 3GPP Release 5; for example, the CREST-2 MME load does not exceed 230 kbytes for 2000 users/km^2 and 12 candidate eNBs, when 15% of the UE population is engaged in CREST-2 signaling.

3 Conclusions

The present thesis proposes the design, analysis, and evaluation of CREST, a novel signaling protocol that offers RAT/spectrum mobility in cognitive wireless networks. CREST improves the quality of service of user sessions via RAT capabilities discovery, spectrum resource negotiation, and in advance coordinated spectrum allocation. The thesis also describes the protocol operation via CORPS, a new modular architecture that can be deployed over the most important and challenging next-generation network infrastructure, 3GPP SAE, with minimal required modifications for network elements and interfaces. A similar migration strategy can be applied for 3GPP2, WiMAX, and All-IP networks.

Results show the efficiency of the protocol in terms of signaling delay and load, as well as signaling-failure probability. Among the key strengths of CREST is its suitability for seamless service continuity in spectrum-agile environments, and the capability to work efficiently in both large geographic areas and geographically limited networks. Furthermore, we have extended the classical notion of call/session-to-mobility ratio, by analyzing the relation between the user session rate and the cognition advertisement rate, as well as the relation between the user mobility rate and the cognition rate.

The thesis also proposes the design and analysis of RSS/RRP, a new signaling protocol and support architecture for mode negotiation and radio-software download, which aim at device reconfiguration in the context of ETSI next-generation networks.

Future work includes evaluation of alternative CREST strategies, and extensions for network sharing and inter-operator spectrum allocation. Assessment of the energy cost in both the user equipment and network elements, when employing the CREST protocol, is an important area for further study.

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