Toward Context-Aware Dynamic Spectrum Management for 5G

Giuseppe Caso, Luca De Nardis, and Maria-Gabriella Di Benedetto

Abstract

5G-specific features, such as massive deployment, heterogeneity, and coexistence, call for innovative dynamic spectrum management mechanisms. Context-aware interoperability and interference control, and their integration, may be crucial to comply with spectrum efficiency and service optimization 5G requirements. Moving from the analysis of research and standardization activities, this article proposes an integrated platform, called C-MIANS, that embeds interference control in standardized context-aware interoperability procedures, toward integration of context awareness into dynamic spectrum management, network selection, and resource allocation.

Introduction

Improving spectrum efficiency by favoring coexistence is inherent to the fifth generation (5G), where dynamic spectrum access (DSA) is the founding access strategy of the wireless resource, allowing different systems to dynamically share the spectrum [1]. Coexistence is present in cellular and complementary networks, forming the 5G architecture.

As regards the cellular network, this will consist of heterogeneous and overlapping segments, referred to as tiers or heterogeneous networks (HetNets). Traditional outdoor macro base stations (MBSs) will be massively overlaid with power-limited small base stations (SBSs), that is femto, pico, and micro BSs, in both the space and frequency domains, with low-priority small cell tiers sharing the wireless resource with high-priority macrocell peers. Resource sharing will also eventually occur among equal-priority tiers. Under tiers' coexistence, spectrum efficiency may be improved by adopting dynamic spectrum management (DSM) mechanisms, such as interoperability between tiers (e.g., offloading and handover) and control of intranetwork interference between different- vs. same-priority tiers, so-called crosstier vs. cotier interference, respectively [2, 3].

Beyond the cellular network, the 5G architecture foresees a mixture of different radio access technologies (RATs) [4]. 5G users will be able to dynamically switch from one RAT to another within the same connection; 5G devices will not only support 3G, 4G, and WiFi, but also 5G standards and device-to-device (D2D) operation mode, which may or may not be coordinated with the cellular network, and will operate across licensed vs. unlicensed frequency bands. The concept of HetNets naturally combines with RAT diversity, leading to multi-RAT HetNets the core of the 5G network, with the inevitable need for implementing DSM toward internetwork interference control and interoperability among networks. As a matter of fact, interoperability between Third Generation Partnership Project (3GPP) networks, and between 3GPP and non-3GPP networks, has appeared since 3G, and was further developed in 4G, as filed in 3GPP standardization activities. In particular, 3GPP Releases 6 and 7 addressed interoperability between 2G and 3G, and between 2G/3G and WiFi, and introduced the I-WLAN framework. Releases 8 and 9 addressed LTE interoperability with previous cellular generations, either 3GPP (GSM/UMTS), 3GPP2 (cdma2000), or IEEE (WiMAX), and with WiFi. Releases 10 to 12 addressed interoperability with LTE-Advanced (LTE-A). Finally, in 2016, the concept of coexistence applied to cellular networks, appearing in Release 13 and reflected in the possibility for a cellular technology to access the unlicensed industrial, scientific, and medical (ISM) bands, which is a prerogative of WiFi and other non-cellular RATs, paved the way for striking and innovative interoperability schemes.

Massive deployment, as foreseen in 5G, exacerbates both intranetwork and internetwork interference, making interoperability and interference control two crucial components of DSM design. The introduction of awareness, based on the collection of context information, may bring benefit to DSM, and give rise to context-aware dynamic spectrum management (CA-DSM) [5]. Information can be retrieved from time, environment, network, user, and other domains, including temporal stamps, positions, distances, mobility patterns, spectrum occupation, active RATs and their quality of service (QoS), traffic type, quality of experience (QoE), power consumption, battery state, and CPU load, to mention a few. Figure 1 shows the domains identified as enablers for the implementation of CA-DSM in 5G.

Cognitive radio (CR) is one of the most promising enablers of CA-DSM. Generally speaking, CR is an intelligent radio, capable of autonomous reconfiguration by learning and adaptation to the surrounding context [1]. Traditionally, CR is most often intended as spectrum sensing. Recent advances in characterizing the environment and

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user/device features, in particular accurate localization, as well as user-centric communication paradigms, are strong add-ons in CR implementation and related context-aware capabilities.

Beyond CA-DSM, recent research activities highlight the need for integrating, and jointly designing, interoperability and interference control, toward the definition of optimal procedures of network selection and related resource allocation. Existing standardized procedures focus, however, on either one aspect or the other. In particular, with the introduction of CA, interoperability standards propose user-centric network selection schemes that are designed in order to satisfy QoE user requirements, and do not consider the effect of the selection in terms of intranetwork and internetwork interference. As a matter of fact, standardized network selection procedures do not embed interference control, which is instead devoted to preserving network status quo, and do not rank admission of new incoming users with high priority.

This article attempts to address this dichotomy by proposing a new platform, referred to as *cognitive media independent access network selection* (C-MIANS), that considers interoperability vs. interference control, by merging the 3GPP *Access Network Discovery and Selection Function* (ANDSF) [6], and IEEE 802.21 *Media Independent Handover* (MIH) [7] network selection protocols, and embedding those with spectrum sensing functionalities, provided by IEEE 1900.6, "Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and Other Advanced Radio Communication Systems" [8]. The proposal follows from the analysis of research and standardization activities toward the definition of CA-DSM for 5G.

The article is organized as follows. Interoperability and interference control for DSM are first analyzed, underlying the benefit of introducing CA and CR paradigms. A description of existing protocols for interoperability, interference control, and their complementarity is also reported. The C-MIANS platform, which integrates the above protocols, is then presented, and its application to network selection is discussed. Final remarks and open challenges conclude the article.

Context-Aware Interoperability

The analysis of the offloading procedure, supported by the handover function, provides interesting insight in the evolution of interoperability between cellular and other networks [9]. Offloading refers, in general, to the possibility of delivering data on different networks, while handover enables the actuation of switching a device from one access network to the other without dropping the connection. Both functions have been extensively analyzed under different aspects: the dichotomy between network- vs. user-driven procedures, the type of context information and decision algorithms, and the degree of cooperation between network entities [10]. In 3G times, offloading and handover were not designed as DSM mechanisms, since DSA and spectrum sharing were not even conceivable for commercial applications, and were basically adopted for improving performance of the cellular network. The status of supporting networks, such as WiFi, was not taken into account; thus, interoperability was context-unaware, and switching was transparent to
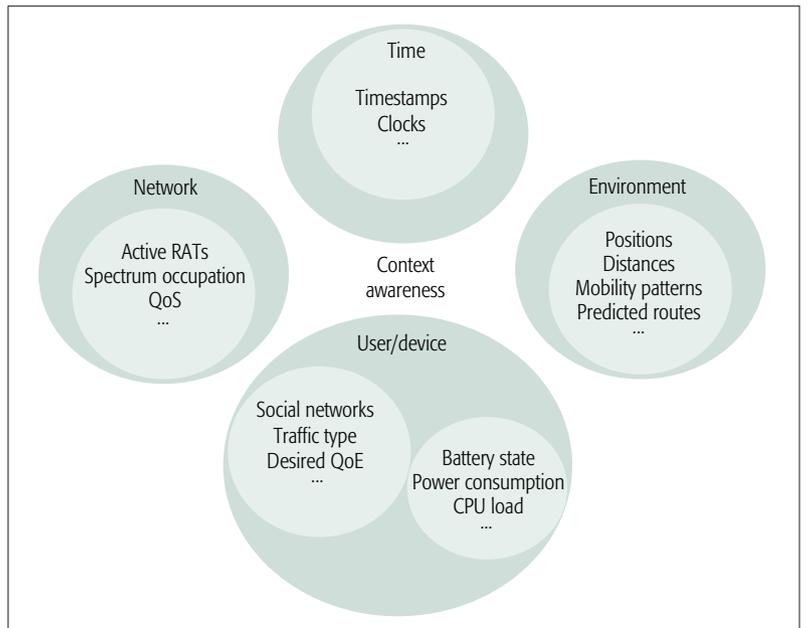

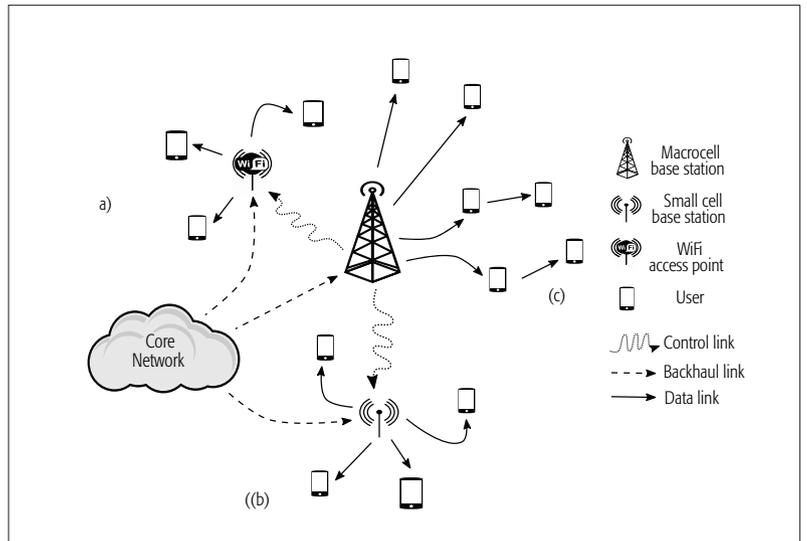FIGURE 1. Identification of domains for the implementation of CA-DSM mechanisms in 5G.

FIGURE 2. Downlink offloading onto: a) WiFi; b) small cell; c) D2D.

status and users' requirements. Small cell offloading was introduced in 4G, with the advantage of no technology switching, leading to management and experience continuity for both operators and users. Novel offloading schemes are currently under investigation in 5G based on the introduction of D2D, as shown in Fig. 2, for downlink offloading onto WiFi vs. small cell vs. D2D.

With the advent of DSA and spectrum sharing, offloading and handover procedures must be envisioned as CA-DSM mechanisms, where operator and user perspectives converge toward the common goal of optimizing access network selection and resource allocation. From this perspective, a trade-off between context retrieval and resource exploitation is required, as analyzed in [11].

CA network selection is currently under analysis in both HetNets and multi-RAT HetNets. In network-driven HetNets, macro and small cell BSs may exchange users with low signal-to-inter-

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Functionality	ANDSF	MIH	Comment
Triggers	---	Event service (ES)	ANDSF does not define handover events, but it uses the event reporting function already deployed within the EPC. MIH defines the events, at both user and network sides, through the ES.
Policies	Intersystem mobility and routing policies (ISMP and ISRP)	---	ANDSF defines the operator policies with respect to handover requests through ISMP and ISRP. MIH does not define policies.
Coarse CA	ANDSF server	Information server	Both ANDSF and MIH define servers in the core network with initial information on the user neighborhood.
Fine CA	User	Network (point of service, PoS)	ANDSF requires context retrieval by users. MIH requires that the users trigger the process, while context retrieval is performed by its PoS.
Final decision	User with operator policies	User	In a user-driven procedure, both standards let the user make the final decision, adopting vendor-specific algorithms. Within ANDSF, the decision also depends on the operator policies.

TABLE 1. ANDSF (3GPP) against MIH (IEEE).

ference-plus-noise ratio (SINR) [2]. In user-driven HetNets, the selection criterion can be refined by adopting reference signal received power (RSRP) and quality (RSRQ), as has been well known since 4G [3]. Network assistance, through the concepts of cell breathing and cell range expansion, is also proposed, where the coverage of BSs is adapted to traffic loads. Regarding multi-RAT HetNets, a cognitive approach for SBSs was proposed in [12] where, based on traffic type, a reinforcement learning algorithm lets SBSs learn and use optimal parameters to access licensed vs. unlicensed bands for delay-sensitive vs. delay-tolerant data, respectively. Position information was included in offloading delay-tolerant traffic in [13].

In terms of standards, increased activity is underway within 3GPP and IEEE toward the definition of CA network selection. In particular, 3GPP proposed the founding concept ANDSF in Release 8 (2011) [4]. The following 3GPP releases further discussed ANDSF, adding procedural schemes and architectural elements, toward its full application. A dedicated entity within the Evolved Packet Core (EPC) was added, called the ANDSF server, which communicates with users via a specific interface named S14. In the user-driven case, once queried by users, with a message containing their positions and capabilities (e.g., supported RATs), the ANDSF server provides three types of so-called services:
- Access network discovery information, consisting of a list of available networks in the user's neighborhood, with corresponding points of attachment (PoAs), which are the physical entities providing connection to users, and adopted carrier frequencies
- Intersystem mobility policy (ISMP), containing the operator policies for selecting the most preferable network when users may activate only one RAT at a time
- Intersystem routing policy (ISRP), containing the operator policies for selecting different networks when users may activate more than one RAT at the same time

The above information is completed with the degree of reliability of the services. This is crucial

considering that ANDSF services are not updated in real time, and operator policies only provide coarse indications. For this reason, users may want to perform context retrieval measurements for each candidate network, and collect indicators such as QoS parameters and position of PoAs.

The efforts within the IEEE community date back to 2009, with the 802.21 standard, also known as MIH [5], which defines three types of services:
- Event services (ES), which specify the events triggering a handover request
- Command services (CS), which enable users to deliver handover messages
- Information services (IS), which provide the capability of context retrieval

Similar to ANDSF, MIH specifies the characteristics of an information server and the PoAs. Moreover, MIH introduces the concept of points of service (PoSs); PoSs are virtual entities, co-located with PoAs in the simplest configuration, that provide message exchange between users and candidate networks, and also manage the context retrieval phase. In user-driven handover, users first send a request to the server in order to obtain preliminary information regarding the surrounding networks, and then connect to the PoSs of their current network. The PoSs initiate a query with PoSs of candidate networks and collect information on network state to be sent back to users, who in turn autonomously select the best network. MIH has been embedded into other IEEE standards, such as WiFi 802.11u, and WiMAX 802.16g. A comparison of the main functionalities of ANDSF against MIH is given in Table 1.

CONTEXT-AWARE INTERFERENCE CONTROL

DSA and spectrum sharing boost the need for intranetwork and internetwork interference control. Besides static interference control, mainly devoted to coordinated frequency reuse, the adoption of CR, supported by spectrum sensing, is currently under investigation for dynamic control.

In the case of HetNets, small cell tiers may access the spectrum in either an overlay or under-

lay fashion. In both cases, small cell tiers first sense the spectrum shared with macrocell tiers. If segments of the spectrum are temporarily free, small cells may occupy them in an overlay mode. Small cells may also adopt an underlay access, that is, use segments already occupied by macrocells, if the generated crosstier interference, which can be adjusted by changing transmission parameters at small cells, is acceptable for macrocells [14]. Regarding cotier interference, cognitive carrier sense multiple access was proposed in [14], where small cells access spectrum segments that are unoccupied by macrocells after further sensing them as free from contending small cells.

Cooperative spectrum sensing (CSS) was also proposed in order to increase reliability of sensing by pooling sensing measurements among neighbors or central units. Measurements are commonly performed by those devices looking for transmission opportunities, mainly SBSs and small cell user equipments (SUEs) in 5G scenarios. For energy efficiency, selecting a subset of cooperating entities, based on device energy status and position, may be crucial. It is possible, however, to consider dedicated sensing entities, activated by SBSs, SUEs, or central units [15].

As regards multi-RAT HetNets, the adoption of additional unlicensed spectrum segments for small cells, such as ISM bands at 5 GHz, toward large-scale deployment has been proposed in 4G, and referred to as LTE-unlicensed (LTE-U) or licensed-assisted access using LTE (LAA-LTE). This scenario introduces internetwork interference between LTE and WiFi. Dynamic time-domain resource sharing has been proposed, in which the LTE-U network istantiates time frames with reduced data and power; the WiFi APs apply sensing to detect those frames and use them for transmission. The scheme, referred to as almost blank subframes (ABSs), can be improved by optimizing sensing thresholds and duration, as well as by enabling LTE cells to estimate interference levels of nearby WiFi APs in a listen-before-talk approach [16][17]. The knowledge of the interference space distribution can, in fact, further optimize resource allocation among heterogeneous entities. In [16], the interference measured by a sensor at known distance from a reference BS was mathematically related to the space distribution, density, and transmitted power of neighboring APs/BSs; this allowed evaluation of the interference at any location within BS coverage and optimization of downlink resource allocation without the need for preliminary coordination with neighboring APs/BSs. In 5G, the challenge raised by coexistence of HetNets and WiFi expands beyond ISM bands, in particular to the 60 GHz mmWave bands, where the IEEE 802.11ad standard, also known as WiGig, is expected to coexist with 5G backhaul links between SBSs and the core network, which are required to support the dense deployment of small cells. Interoperability between cellular and WiFi must therefore be supported by cognitive interference control.

Standardization of CR functionalities is pursued by IEEE, as addressed by the IEEE P1900 Standards Committee (2005), reorganized in 2010 as the Dynamic Spectrum Access Networks Standards Committee (DySPAN-SC). Their activities led to the definition of a suite of standards named IEEE 1900, defining CR methods and application scenarios. In particular, IEEE 1900.6 (2011) defined spectrum sensors, data archives, and cognitive engines, as well as their procedures, protocols, and interfaces, and may thus play a major role in interference control in 5G [6].

COMBINING INTEROPERABILITY AND INTERFERENCE CONTROL: C-MIANS

The main goal of the C-MIANS platform is to embed interference control in standardized CA interoperability procedures toward the integration of CA-DSM mechanisms in network selection and resource allocation. The proposal is to merge ANDSF and MIH standards, and to embed within the spectrum sensing provided by IEEE 1900.6.

C-MIANS PROCEDURE AND PLATFORM ARCHITECTURE

The C-MIANS procedure consists of either network- or user-driven network selection, and foresees three phases:
• Network discovery and context retrieval, during which candidate networks are discovered, and their status is collected. Furthermore, their associated spectrum is sensed in order to derive information on the interference currently affecting each resource segment.
• Network decision, during which the involved entity selects one of the candidate networks. This is done by considering acquired context information, expected QoE, and operator policies.
• Connection execution is the phase during which the entity switches its connection toward the selected network.
 The corresponding architectural components are:
• The user vs. the access node of the current network, which are the physical entities triggering user vs. network-driven procedures
• A context retrieval system, composed of entities collecting information related to candidate networks and corresponding spectrum segments
• A control system, composed of entities dedicated to information dissemination during the procedure

COMPATIBILITY WITH STANDARDS

C-MIANS components are compatible with ANDSF, MIH, and IEEE 1900.6 standards. The user is ANDSF/MIH compatible, while the access node of the current network, which acts as PoA/PoS, data archive, and cognitive engine, is MIH/IEEE 1900.6 compatible. The context retrieval system also includes an ANDSF server and other MIH/IEEE 1900.6 entities. Some of these entities, called spectrum agents (i.e., energy detectors in the simplest configuration) collect spectrum information only, acting as MIH non-PoSs and IEEE 1900.6 sensors, while others collect candidate networks' information and act as PoSs. The control system does not require any additional physical component, since it is formed by the same entities as the context retrieval system, exchanging information via ANDSF, MIH, and IEEE 1900.6 interfaces.

 The C-MIANS procedure is compatible with standards as well, since it considers, as triggers, events that are specified in the MIH event service and can be roughly classified in physical (PHY)/

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When confronted with standards, the platform requires a limited signaling overhead, due to the use of spectrum agents for sensing. Moreover, energy consumption of the communication network is not increased, since spectrum sensing is performed by a dedicated infrastructure.
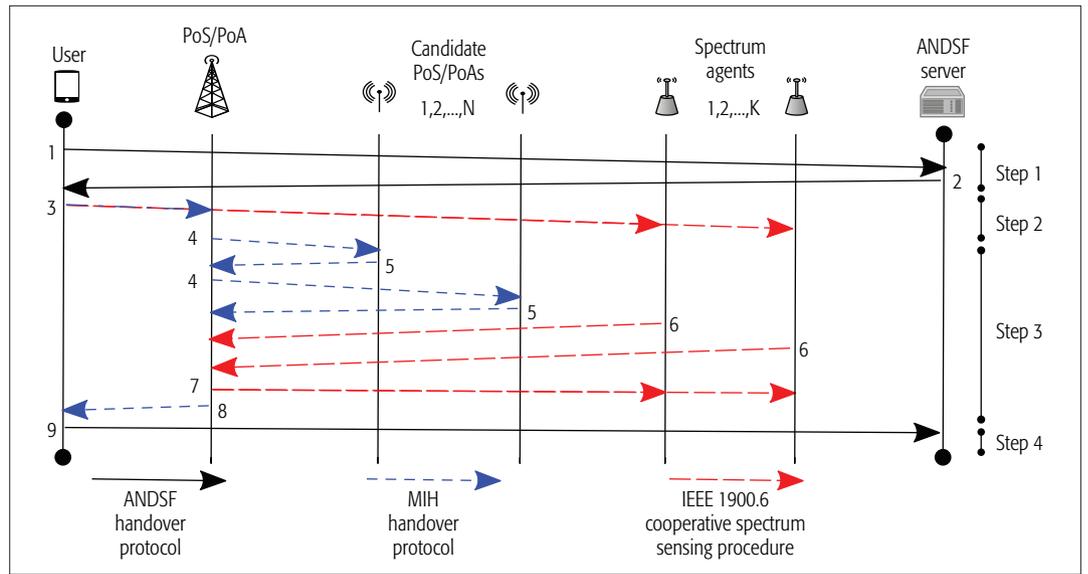

FIGURE 3. C-MIANS protocol, including message exchange and involved network entities.

medium access control (MAC) vs. higher layer events, such as link up and link down vs. QoS decrease and QoE request.

Without loss of generality, consider the case of user-driven network selection, illustrated in Fig. 3. As shown in figure, the procedure includes ANDSF, MIH, and IEEE 1900.6 functions.

Step 1 (ANDSF Activation): The user connects to the ANDSF server via S14 interface, and receives coarse context information and operator policies in the form of access network discovery information and intersystem mobility/routing policies.

Step 2 (MIH and IEEE 1900.6 Activation): A MIH message is used by the user to trigger fine context retrieval to its PoS, and spectrum sensing to its nearby spectrum agents. The message is sent through MIH RP1 and RP3 interfaces, that connect users with PoSs and non-PoSs, respectively.

Step 3 (Context Retrieval and Candidate Networks Evaluation): The PoS connect to PoSs of candidate networks and receives context information via MIH RP5 interfaces that connect the PoSs. The PoS also receives sensing results from spectrum agents via MIH RP4 interfaces that connect PoSs with non-PoSs, and combines them in order to evaluate the status of each segment. RP4 interfaces also act as IEEE 1900.6 CE/DA-S interfaces, connecting cognitive engines to sensors. Finally, the PoS deactivates spectrum agents via RP4 and transfers the full acquired information to the user via RP1.

Step 4 (Network Decision and Connection Execution): The user selects the best network by applying a decision algorithm, possibly vendor-specific, that combines information provided by its PoS, ANDSF policies, and its own QoE preferences. Then it initiates the connection execution procedure by informing the ANDSF server via S14, and current and selected PoSs via RP1.

When confronted with standards, the platform requires limited signaling overhead due to the use of spectrum agents for sensing. Moreover, energy consumption of the communication network is not increased since spectrum sensing is performed by

a dedicated infrastructure. Table 2 summarizes the components and involved standards within each phase of the procedure.

C-MIANS Context Awareness

The C-MIANS platform allows the application of enhanced schemes of dynamic network selection and resource allocation through the collection of heterogeneous context information, such as:
- User parameters: position, distance from PoAs, required QoE, and power load
- Network parameters: QoS indicators, such as data rate, delay, jitter, loss, and throughput
- Spectrum parameters: indicators of the interference affecting the candidate spectrum segments

Considering ANDSF and MIH standards, the proposed innovation lies in the use of information related to interference levels within the network selection procedure. Most often, interference measurements, such as RSRQ at the user side vs. SINR and received interference power (RIP) at the BS side, are used in network-driven cellular offloading and resource allocation once a serving network is selected [2, 3, 16]. A few proposals do take into account interference-related metrics in handover decision algorithms by comparing the measured SINR of the current network against the estimated SINR of candidate networks before a final decision [10]. C-MIANS extends this concept, since it is capable of operating with interference levels that are measured rather than estimated for all candidate networks. A beneficial win-win mechanism between users and candidate networks may also be triggered by the C-MIANS procedure. In the user-driven case, for example, after the PoSs receive the interference information, users are likely to select networks with low, rather than high, interference levels, with the benefit of limited impact on networks affected by high interference.

CA network decision can be integrated in C-MIANS and enhanced by the sensing functionalities offered by the platform. The collection of multiple context information allows the application of multi-criteria, multi-attribute decision making (MCDM, MADM) algorithms, which are proved

to perform better than common RSRP ones in terms of QoS, QoE, and ping-pong effects [10]. In C-MIANS, MCDM and MADM algorithms can incorporate interference measurements in the decision, allowing for the definition of different, possibly vendor-specific, utility and cost functions for network selection.

CONCLUSION

This article analyzes research and standardization activities in the context of DSM for 5G, and discusses the need for integrating context-aware interoperability and interference control toward the optimization of dynamic network selection and resource allocation. An integrated platform, called C-MIANS, is proposed. The platform merges, in a potentially energy-efficient manner, 3GPP ANDSF and IEEE MIH network selection protocols, embedding, within, the IEEE 1900.6 spectrum sensing protocol. C-MIANS procedure, architecture, and compatibility with standards are analyzed, and the advantage of using the platform is discussed, underlying the possibility of enabling network selection based on a win-win mechanism between users and networks. The possibility of applying different CA multi-criteria decision algorithms within the platform, and of enhancing those through interference measurements, is also highlighted.

Several research lines toward CA-DSM, are open for future investigation. In particular, interference dynamics and related spatial distribution should be explored in light of their application to physical layer optimization, such as link adaptation and signal precoding, up to service optimization, such as network slicing, and massive MIMO 5G scenarios.

As regards the platform, experimental analysis is needed in order to quantify the performance gain that can be obtained with interference-enhanced network decision algorithms at both the user and network sides. Moreover, the trade-off between context retrieval, signaling overhead, and resource exploitation should be experimentally tested, and optimal platform configurations should be derived for different application scenarios, such as high mobility and ultra-dense coexistence.

ACKNOWLEDGMENT

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Phase	Architectural components	Standards (interfaces)
Network discovery and cContext retrieval	User and current PoA/PoS, context retrieval system, control system	ANDSF (S14), MIH (RP1, RP3, RP4, RP5), IEEE 1900.6 (CE/DA-S)
Network decision	User and current PoA/PoS	(Vendor-specific)
Connection execution	User and current PoA/PoS, control system	ANDSF (S14), MIH (RP1)

TABLE 2. C-MIANS platform: phases, involved architectural components, and standards (with corresponding interfaces).

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