July 2012, Vol. 50, No. 7

IEEE Communications MAGAZINE

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TOPICS IN NETWORK AND SERVICE MANAGEMENT

Cognitive Control Channels: From Concept to Identification of Implementation Options

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ABSTRACT

Recent effort related to cognitive radio systems has lead to an in-depth analysis of context information management and exploitation based on a cognitive control channel for enhancement of management needed for, say, suitable link selection in a heterogeneous radio framework, dynamic radio resource management, and distributed sensing. Concerning the actual implementation of such a CCC, the focus was recently moved toward an in-band solution, where the information is transported building on existing radio access technologies. In this scope, this article illustrates relevant technical scenarios in which CCCs can be exploited and outlines a set of derived system requirements. The article provides an overview of various possible RAT independent and dependent implementation options, such as Diameter, distributed agents, 3GPP radio resource control (RRC) mechanisms, IEEE 802.21, IEEE 802.11, WiMedia UWB, and Bluetooth. The advantages and drawbacks of the various options are discussed.

INTRODUCTION

The cognitive control channel (CCC) has been identified as a key feature required for the efficient operation of cognitive radio Systems (CRSs). In general, a CCC can be defined as a channel for transmitting elements of information necessary to manage and realize various operations within a CRS. Information may be conveyed from network infrastructure elements to user equipment. Furthermore, the concept of such a CCC may be exploited for the exchange of information between terminals to increase the accuracy of obtained knowledge on the context of the environment. The role of one such CCC, the cognitive pilot channel (CPC), has first been studied for the specific context of heterogeneous CRSs [1] and has been introduced as input to the International Telecommunication Union, Radiocommunication Sector (ITU-R) within the matter of addressing regulatory measures to enable the introduction of software-defined radio (SDR) and CRS. The CPC provides information from the network to the terminals on, for example, frequency bands, available radio access technologies (RATs), and spectrum usage policies, with the aim of facilitating the network discovery and selection process in composite radio networks under flexible spectrum management. The concept of the CPC has then been further extended to also include the concept of exchange of cognitive data among user devices [2]. These studies were exploited as inputs to standardization: the IEEE Dynamic Spectrum Access Networks (DYSPAN) Standards Committee (formerly IEEE Standards Coordinating Committee 41 [SCC41]) published the IEEE 1900.4 standard [3] in 2009 related to the efficient operation of heterogeneous CRS by introducing a CCC in the form of a so-called *radio enabler*. Specifically, the standard introduces an information model at the application layer based on an object-oriented approach and addresses a heterogeneous wireless communication framework. Corresponding studies were also undertaken in the context of the European Telecommunications Standards Institute Reconfigurable Radio Systems Technical Committee (ETSI RRS TC) (ETSI TR 102.683, v1.1.1, "Reconfigurable

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Radio Systems [RRS]; Cognitive Pilot Channel [CPC]," 2009). In recent years, a number of papers have been published detailing usage examples and advantages of such a channel. For example, [4] illustrates how a CPC may be exploited for orchestrating a heterogeneous indoor environment, user-context-dependent virtual connectivity maps are introduced in [5] and details are provided on how the behavioral statistics of a radio node can be modeled based on Markov-models whose parameters can then be distributed via a cognitive channel. The ways in which such a channel can be straightforwardly exploited for distribution and collection of radio measurements, etc are illustrated in [6]. Various business model aspects of the CPC as an instantiation of the broader CCC concept have been studied [2] and a quantitative analysis of costs and gains has been performed [7, 8]. While the conceptual framework for the CCC has been thoroughly considered in the past, plans and options with respect to implementation need to be addressed.

To this end, the ETSI RRS TC has suggested two principal ways forward:

- In-band CPC: Cognitive data is transported on top of an existing RAT; either using a separate control channel or an existing one by adding, say, specific IP-based CPC packets.
- Out-of-band CPC: A dedicated physical channel is defined for the distribution of cognitive data.

The latter option has been extensively discussed at the ITU-R level, since it requires the reservation of a (globally harmonized) cognitive frequency band. However, broad support has not been gained, and the consideration of such a physical channel has been put on hold. Therefore, this article focuses on potential implementation options for an in-band channel approach and presents several possible solutions that are either RAT-independent (i.e., RAT protocols are not modified) or RAT-dependent (i.e., CCC is supported as an extension of particular RAT protocols).

While the concept and role of CCC in the operation of CRS have been studied from various aspects in research and standardization activities, the study of actual implementation options is relatively recent (ETSI TR 102 684 V1.1.1, "Reconfigurable Radio Systems [RRS]; Feasibility Study on Control Channels for Cognitive Radio Systems," 2012). The investigation of implementation options is a crucial step toward the realization of the CCC and the deployment of CRS. In this direction, this article provides an overview of potential implementation options based on requirements derived from a variety of technical scenarios.

The rest of the article is organized as follows. We give an overview of the technical scenarios for the exploitation of the CCC. We outline the main system requirements for CCC derived from the technical scenarios and highlights relevant, indicative CCC messages. An overview of possible implementation options is provided. We elaborate on advantages and drawbacks of the various options. Finally, we conclude the article with a summary of the main points.

Technical Scenarios

The role of the CCC is to enable exchange of information between network elements and terminals in a CRS. The aim is to enable the cooperation between heterogeneous technologies, the coordination of infrastructure and devices, as well as increase the accuracy of the obtained knowledge on the context of the environment and consequently enhance the efficiency of the CRS operation in various scenarios. The CCC can be seen as an enabler for providing information (e.g., frequency bands, available RATs, and spectrum usage policies) from the network to the terminals (and vice versa), as a channel for the exchange of cognition related information between terminals, and as a channel for the exchange of information between network elements (Fig. 1).

Four technical scenarios in which the CCC concept can be exploited are described in this section to provide more detail on the type of information that may be exchanged between network elements and terminals in the scope of a CRS.

The CCC can be seen as an enabler for providing information from the network to the terminals (and vice versa), as a channel for the exchange of cognition related information between terminals, and as a channel for the exchange of information between network elements.

Coordination of Diverse Radio Networks and Nodes in Cases of Unlicensed Spectrum or Secondary Spectrum Usage

Current user devices (e.g., smartphones) can simultaneously use heterogeneous RATs, operating in licensed frequencies as well as unlicensed frequencies. For licensed frequencies, where technologies like Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE) are used, a certain quality of service (QoS) can be guaranteed because the usage of the radio resources at a given frequency is controlled exclusively by one network. In unlicensed frequency bands, where technologies like WLAN and Bluetooth are used, networks are uncoordinated and may interfere with each other; thus, the user must tolerate QoS degradation. A similar situation may occur in cases of secondary spectrum usage (e.g., in the upcoming usage of UHF TV white space frequency bands). Such situations, where different networks and/or nodes use the same frequency bands, can be improved by first exchanging data on the radio resource usage, as well as distributed spectrum sensing results, and then acting on these results by improving the spectrum selection decisions (Fig. 1). The main scope of the CCC is such an information exchange on radio resource as well as spectrum usage. In addition, the CCCs may be used for the negotiation of spectrum usage between different networks. The CCCs will be used between terminals as well as between a terminal and infrastructure networks. This can greatly decrease the spectrum sensing time and required power, and ensure that secondary systems adhere to the regulatory framework.

Managing Single-Operator Multiband, Multi-RAT Networks for Load Balancing and Optimal QoS Provisioning

Operators running and exploiting multiple RATs in heterogeneous multiband (e.g., licensed IMT-band) are expected to significantly

The CCC should support mechanisms to transmit information to a single node identified via an address, e.g., via unicast or dedicated mechanisms. Such a peer-to-peer connectivity should be supported also in cases without the existence of a direct link between the two communicating nodes.

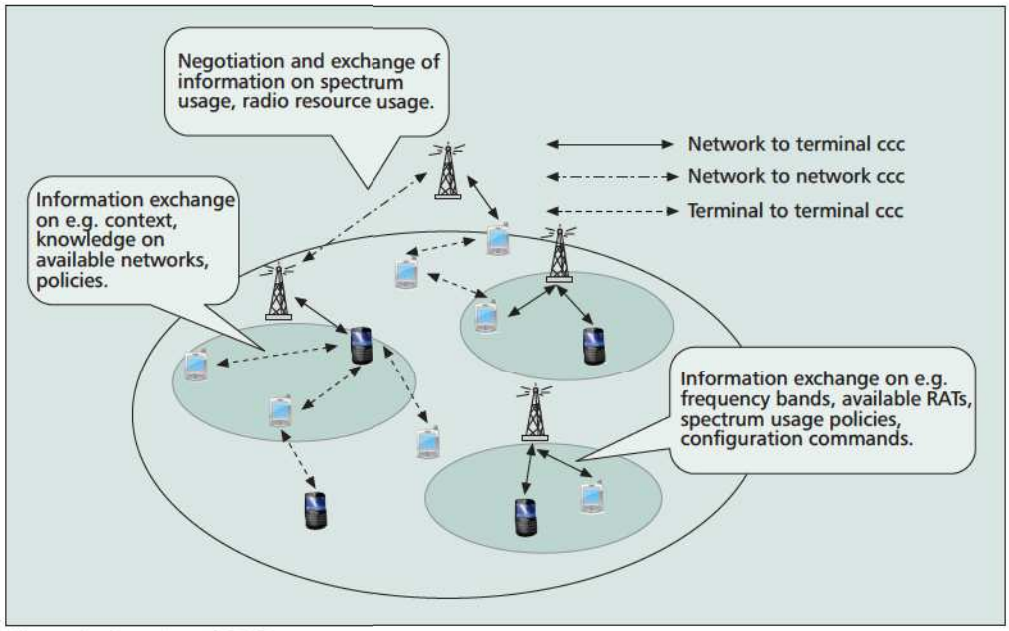

Figure 1. *Overview of CCC concept.*

benefit from balancing the active access networks in order to provide QoS for each customer taking, say, location and mobility into account. In this scenario, the CCC acts as an enabler to inform the devices about spectrum and RAT opportunities providing seamless end-to-end QoS of one operator as well as to stimulate efficient sensing and reporting from the terminals to the networks.

Startup Information Provisioning in an Unknown Environment

In a flexible spectrum management scenario, a terminal may start up in an unknown environment, where it has no knowledge about the RATs and the corresponding, available, and/or used frequency bands, which may actually change dynamically in the geographic location where the terminal is located. Thus, the terminal must scan the whole frequency band to acquaint itself with the spectrum constellation, which is a huge power- and time-consuming task, and might not be efficient in some cases (e.g., due to hidden nodes or receive-only devices). For such a scenario, the network may provide relevant information such as available operators and RATs via a CCC in order to initiate an efficient communication session (ETSI TR 102 684 V1.1.1).

Cognitive Management of Opportunistic Networks

Another envisaged use of CCCs is for enabling the collaboration of cognitive management systems in terms of exchanging information and knowledge with the aim of managing opportunistic networks [9]. In this case, an opportunistic network can be seen as an operator-governed temporary extension of the infrastructure, which involves both terminals and nodes of the infrastructure and is dynamically created for exploiting resource "opportunities." Specifically, these opportunistic networks can be used e.g., for opportunistic coverage extensions of infrastructure networks as well as for opportunistic capacity extensions [9]. In this case, CCCs can be used for the coordination of cognitive management systems for managing the phases of the life cycle of such opportunistic networks (i.e., suitability determination, creation, maintenance, and termination).

System Requirements for Cognitive Control Channels

This section outlines the system requirements for the CCC, which have been derived from the analysis of the aforementioned technical scenarios. The identified requirements have been classified into six categories, which are analyzed in the following subsections.

General Requirements

Communication with the infrastructure: The CCC should allow terminals to directly or indirectly communicate with the infrastructure. This is relevant to all scenarios.

Communication between terminals: The CCC should allow terminals to directly or indirectly communicate with each other. This is relevant mainly to scenarios 1 and 4.

Versatile RAT use: The CCC should be usable for different types of radio access technologies to enable operation of different types of homogeneous as well as heterogeneous networks. The CCC should therefore provide radio-technology-independent mechanisms. However, radio technology intrinsic mechanisms (e.g., to broadcast certain information) may also be supported. This is relevant to all scenarios.

Requirements Related to Terminals

Mobility: The CCC also needs to be robust during user mobility. This means that the CCC should be robust against packet errors, node disappearance, and so on. The CCC should therefore allow reliable transfer of information. This is relevant mainly to scenarios 1 and 4.

Relaying: The CCC should allow forwarding of relevant signaling messages. The forwarding capabilities should be provided for homogeneous as well as heterogeneous networks. This is relevant mainly to scenario 4.

Protocol Requirements

Information provision: The CCC should support the exchange of different types of information relevant operations within a CRS (including the management of opportunistic networks). This information includes context information, policies, decisions as well as pure signaling data and should be encoded compactly to minimize the signaling load.

Unicast and multicast addressing: The CCC should support mechanisms to transmit information to a single node identified via an address (e.g., via unicast or dedicated mechanisms). Such a peer-to-peer connectivity should be supported also in cases without the existence of a direct link between the two communicating nodes (forwarding of signaling data shall be possible). The CCC should also support mechanisms to transmit information to several nodes (e.g., via broadcast or multicast mechanisms).

Secure and unsecured communication: The CCC should allow for unsecured as well as secure data transmission, depending on the confidentiality of the data.

CCC efficiency: The amount of signaling should be minimized.

Protocol requirements are relevant to all scenarios.

Implementation Requirements

The reuse of existing protocols should be considered. Open, extensible protocols are preferred. The CCC shall be capable of supporting several simultaneous signaling transactions per node. This applies to all scenarios,

Requirements Related to Legacy Radio Systems

Preservation of legacy radio systems operation: The impact of CCC on the operation of legacy radio systems should be minimized. The CCC should minimize the impact on the "anchor" network, in terms of mobility (idle and connected), spectrum use, security/privacy, and charging/billing.

Compatibility with legacy radio systems deployments: The impact of CCC on the legacy radio systems deployments should be minimized. The CCC deployment should remain compatible with legacy and foreseeable radio systems deployments/planning techniques (e.g., overlays of macro/femto/relay).

The two aforementioned scenarios are relevant to all scenarios.

Opportunistic Network Management Requirements

The CCC should provide communication means to enable the realization of the management procedures related to opportunistic network (ON) suitability determination, creation, maintenance, and termination (this includes enabling on-the-fly negotiations and agreements). The CCC should provide means for the exchange of ON relevant information within the network of a single operator. The exchange of ON relevant information between operators may optionally be supported. This is relevant mainly to scenario 4.

Indicative CCC messages, which are relevant to the described scenarios and the corresponding derived requirements, include Information Request, Information Answer, and Information indication. These are used to obtain and exchange information between nodes, such as Neighborhood Information, Node status, Node capabilities, User profile, Geographical Location, Policies, and Link Measurements. Further indicative messages related to the management of the life cycle of an ON include ON Suitability Indication, ON Creation Request/Answer, ON Modification Request/Answer, ON Release Answer, and ON Status Notification. Basic CCC data structures comprised in these messages include terminal, base station, user, and operator profiles; base station and terminal context; cognitive management decisions relevant to the infrastructure, terminals, or ONs; knowledge on context and decisions made in the past; as well as policies.

Potential Implementation Options for Cognitive Control Channels

This section addresses various approaches to the potential implementation of the CCC concepts. These are divided into RAT-independent and RAT-dependent options. It should be noted that the type of information exchanged over CCC (i.e., the elementary messages briefly introduced in the previous section) is the same for all implementation options (although obviously, for each implementation option, the format of the message in which the CCC information is encapsulated is different).

Radio-Access-Technology-Independent Implementation Options

IETF Diameter — The Diameter base protocol is an extensible protocol originally designed to provide an authentication, authorization, and accounting (AAA) framework for applications such as network access and IP mobility. Diameter is also used in 3GPP-based networks (ETSI TS 129 229, "Digital Cellular Telecommunications System [Phase 2+]; Universal Mobile Telecommunications System [UMTS]; LTE; Cx and Dx Interfaces Based on the Diameter Protocol; Protocol Details [3GPP TS 29.229]"). CCC messages and parameters can be defined as

CCC implementation options are divided into RAT-independent and RAT-dependent. The type of information exchanged over CCC is the same for all implementation options (although obviously for each implementation option the format of the message in which the CCC information is encapsulated is different).

Within a multi-agent context CCC can be seen as a RAT agnostic upper-layer logical communication channel between distributed agents in both terminal and network sides and used for the conveyance of context information.

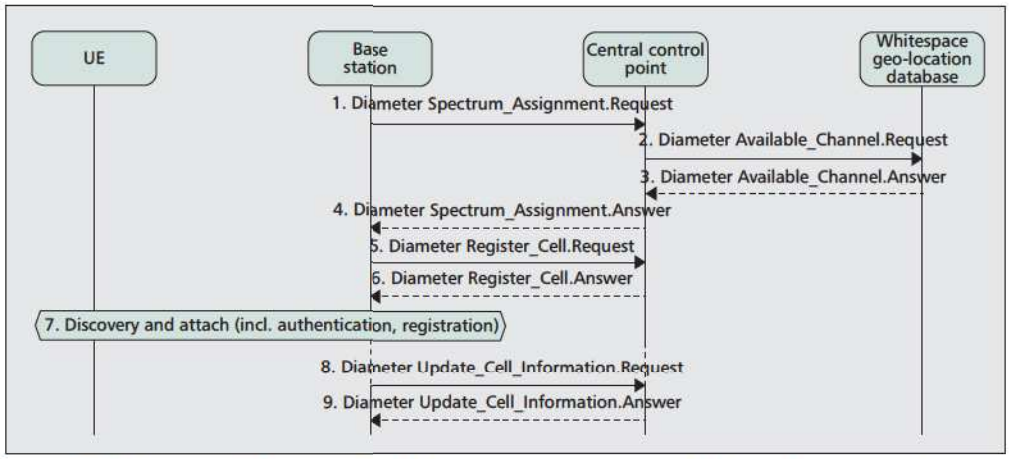

Figure 2. *Indicative use of Diameter as a CCC implementation option for obtaining information in cases of unlicensed spectrum or secondary spectrum usage.*

extensions to the Diameter base protocol. It is worth noting that Diameter itself does not provide any information model. A possible information model for the Diameter approach could be based on the IEEE 1900.4 standard. Figure 2 depicts an indicative CCC message exchange for obtaining information in cases of unlicensed spectrum or secondary spectrum usage when Diameter is employed as an implementation option. More specifically, the figure illustrates an indicative use of Diameter to access a white space geo-location data base.

3GPP ANDSF — For the support of multi-access network scenarios with intersystem mobility between 3GPP networks (GSM, UMTS, LTE) and non-3GPP networks (e.g., WLAN, WiMAX), 3GPP defines the so-called access network discovery and selection function (ANDSF), which is located in the 3GPP Evolved Packet Core (EPC) ((ETSI TS 124 312, "Universal Mobile Telecommunications System [UMTS]; LTE; Access Network Discovery and Selection Function [ANDSF] Management Object [MO] [3GPP TS 24.312 Release 8]"). The ANDSF provides intersystem mobility policies and access-network-specific information from the network to the user equipment (UE) in order to assist the mobile node in performing intersystem handovers. This set of information can be either provisioned in the UE by the home operator or provided to the mobile node (MN) by the ANDSF. In 3GPP Release 8, the ANDSF is located in the subscriber's home operator network (H-ANDSF), while in 3GPP Release 9, the ANDSF can also be located in the visited network (V-ANDSF).

The information distributed between the ANDSF and the UE is defined in the ANDSF management object (MO), which is compatible with the OMA Device Management (DM) protocol specifications version 1.2 and upwards as defined in the OMA DM Device Description Framework described in the "Enabler Release Definition for OMA Device Management." This OMA DM is based on the Synchronization Markup Language. Typically, the ANDSF MO is transported over the OMA DM over HTTP over TLS over TCP over IP. It is worth mentioning that OMA DM also considers information transfer over short-range radio links (i.e., Bluetooth transfer over the Object Exchange, OBEX, protocol).

Distributed Agents — Within a multi-agent environment, every component (e.g., network infrastructure element, user device, and management software) can be represented by one or more intelligent agents that act as a mediator between the components' functionality and the rest of the system. Thus, each system component is loosely coupled to others and can interact by exchanging messages through high-level interfaces. In such a context, CCC can be seen as a RAT-agnostic upper-layer logical communication channel (mainly over TCP/IP) between distributed agents/agent platforms residing in both terminal and network sides and used for the conveyance of context information.

The Foundation for Intelligent Physical Agents (FIPA) is an international non-profit association of companies and organizations with the aim of generating specifications of generic agent technologies. FIPA work can be used to provide a standardized, transport solution for CCC communication. FIPA has defined a number of standard Message Transport Protocols (MTPs) and MTP interfaces to promote interoperability between agent platforms. The Java Agent Development framework (JADE) is a robust, fully FIPA-compliant framework for developing distributed agent systems, and can run on PCs and wireless devices. JADE components exchange messages, which are serialized and transmitted over TCP, according to the FIPA Agent Communication Language (ACL) message structure specification. Figure 3a depicts a view of a CCC message for ON creation implemented as an ACL message in the JADE platform.

In the case of interplatform communication, the following MTPs are currently available for interaction among agents:

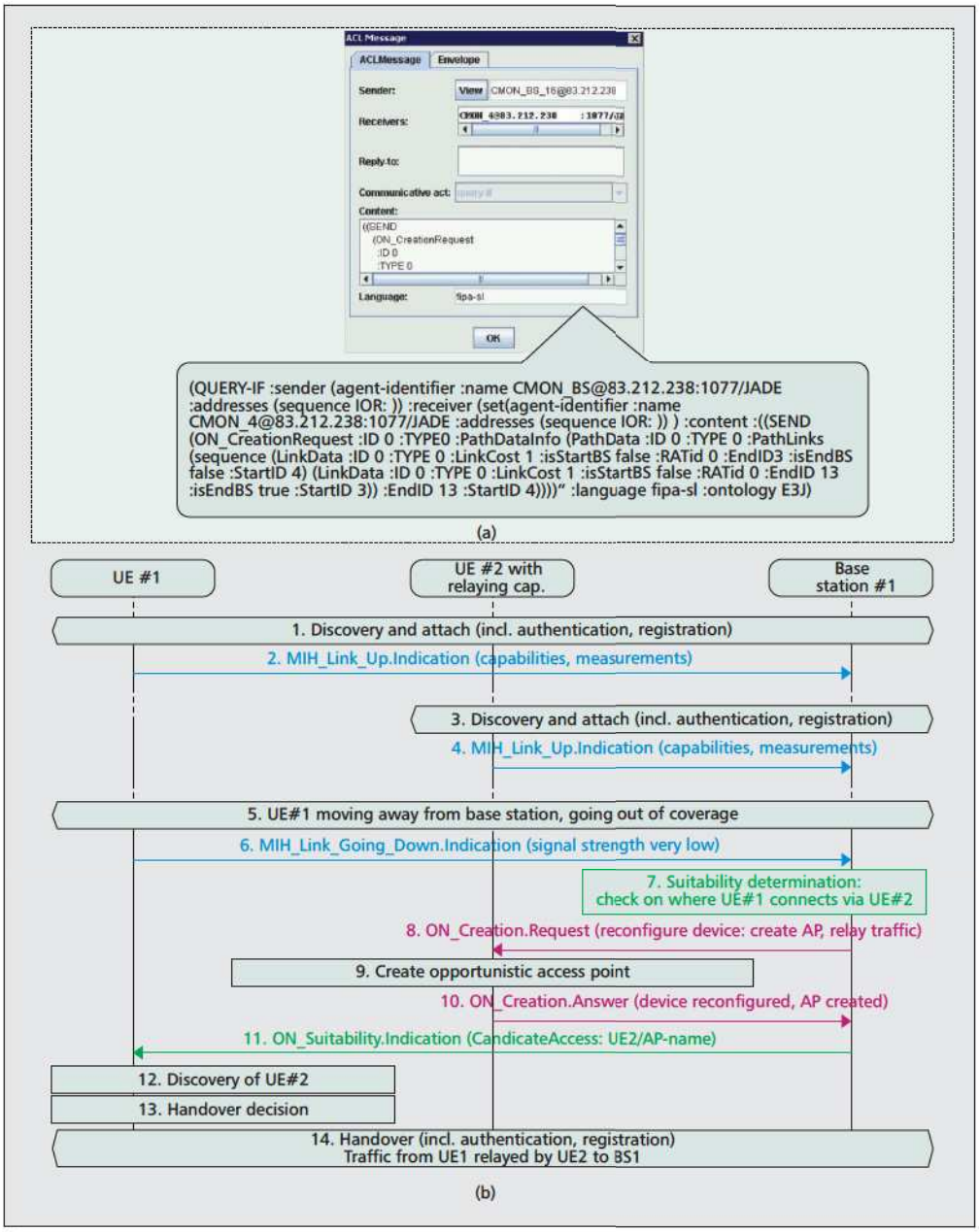

Figure 3. *Indicative view of CCC messages for ON creation and setup: a) use of ACL messages in JADE; b) use of IEEE 802.21.*

- CORBA Internet Inter-Object request broker Protocol (IIOP) MTP based on standard Sun ORB provided with Java (the default installation)
- CORBA IIOP MTP based on ORBACUS
- HTTP-based MTP

IEEE 802.21 — The IEEE 802.21 "Media-Independent Handover (MIH) Services" standard [10] provides a set of extensible mechanisms targeted to enable the optimization of handovers between heterogeneous IEEE 802 systems as well as facilitate handovers between IEEE 802 and cellular systems (e.g., 3GPP and 3GPP2). The standard defines: a new functional entity (MIH Function, MIHF) within terminals and networks; a set of media-independent and media-dependent service access points (SAPs) for information exchange between a MIHF entity and other collocated system functional entities (e.g., link and network layer entities); and a signaling protocol (MIH Protocol) for message exchanging between remote MIHF entities.

The MIHF entity controls link layer operation through media-dependent SAPs and offers services to upper layers entities of the protocol stack (denoted as MIH users) through a media-independent SAP. Services provided to MIH users are classified as Media Independent Event

The MIHF entity controls link layer operation through media-dependent SAPs and offers services to upper layers entities of the protocol stack (denoted as MIH users) through a media-independent SAP.

In order to include cognitive control data, a new SIB Type could be introduced for corresponding information broadcast. The introduction of a novel SIB Type needs to be discussed and agreed within 3GPP; thus, the approach requires the submission of a corresponding Change Request to 3GPP.

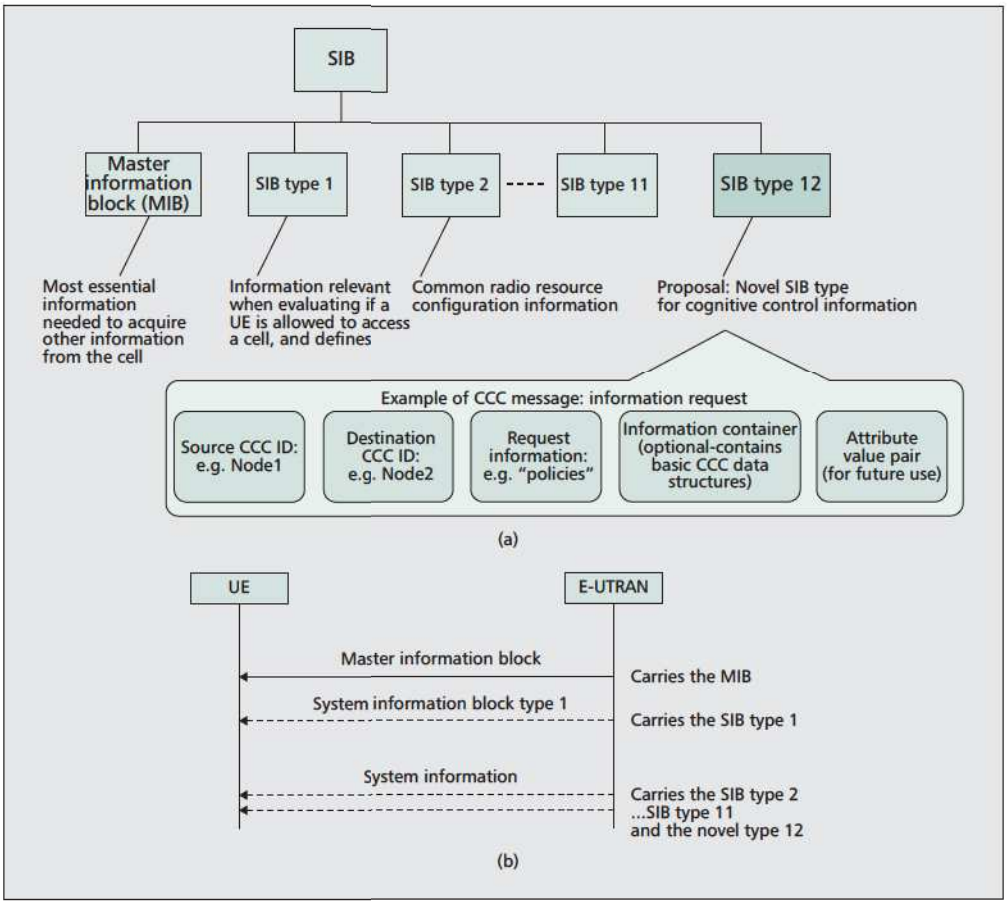

Figure 4. *a) Proposal for introduction of a novel SIB type for provision of cognitive control Information; b) RRC information exchange, including the novel SIBType12 for cognitive control data.*

Service (MIES), Media Independent Command Service (MICS) and Media Independent Information Service (MIIS). MIES provides a service to configure event-triggering rules and transfer event notifications, MICS provides a service to invoke commands between MIHF entities (e.g., handover commit command), and MIIS provides mobile terminals with details on the (static) characteristics and services of the serving and neighboring networks (network type, operator identifier, frequency bands, etc.). IEEE 802.21 defines a complete protocol for message exchanges between remote MIH entities to support aforementioned services. The MIH protocol is transport-agnostic so that MIH signaling messages can be transferred by means of either layer 3 (L3) or layer 2 (L2) protocols.

The implementation of CCC based on IEEE 802.21 would require various extensions. One extension would be the specification of new MIIS information elements (IEs). The current list of specified IEs covers:

- General and access network specific information
- Point of attachment specific information
- Other information that is access network specific, service specific, vendor/network specific

While some of these IEs can be useful in the framework of CCCs, new IEs for further context awareness information to be distributed among different cognitive nodes (e.g., transfer of spectrum opportunities for secondary access) need to be defined. Another extension would be the specification of a new set of MICS "commands" and MIES "events" tailored to support the necessary procedures required for the operational control and management of a CR network. In addition, extensions enabling a distributed communication model encompassing terminal-to-terminal communication would be necessary. The current MIHF communication model is limited to MIH information exchanges between a MIHF entity in the terminal and a set of MIHF entities within serving and neighboring networks.

Figure 3b presents an indicative message sequence for the use of IEEE 802.21 for the setup of an ON.

Radio Access Technology Dependent Implementation Options

3GPP RRC — For cellular communication systems according to 3GPP's variants of radio access technologies (GSM/EGDE, UMTS/HSPA, LTE/LTE-Advanced), a straightforward approach to transmit cognitive control data would be to enhance system information (SI) broadcast messages.

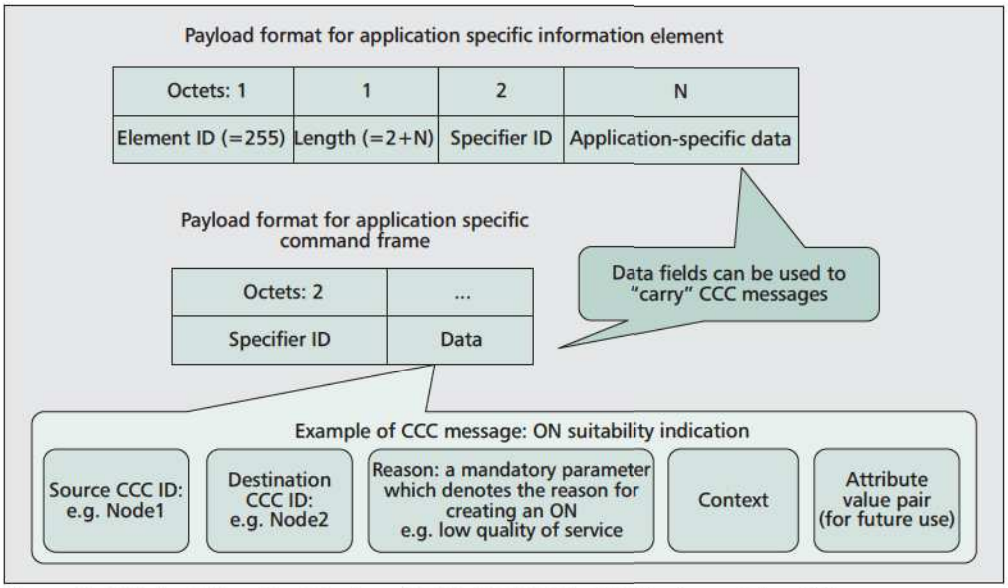

Figure 5. *High-level view of exploitation of WiMedia UWB for CCC implementation [12].*

The exchange of CCC data between IEEE 802.11 devices can be achieved by exploiting VSIEs where CCC information is included as IEs in management frams such as beacons or probes. Alternatively, VSA frames can be exploited, where CCC information is carried using new standalone management frames.

For instance, in case of LTE there are three types of RRC messages for SI-Broadcast, and the following channel mapping applies [11]:

- Channel mapping applicable for the master information block (MIB)
- Channel mapping applicable for all the other system information blocks (SIBs)

The MIB contains the most essential information needed to acquire other information from the cell. For the MIB and SIB-Type1, distinct RRC messages have been defined, while SIB-Type2 through SIB-Type11 use a third type of RRC messages. At the time of writing this article, 11 SIB-types were available. In order to include cognitive control data, a new SIB Type could be introduced (SIB Type 12: cognitive control data) for corresponding information broadcast. Figure 4a depicts the proposed introduction of an additional SIB Type 12, while Fig. 4b shows in a high-level manner the final RRC information exchange (including the proposed additional SIB Type 12) between the E-UTRAN network and the UE. The introduction of a novel SIB Type needs to be discussed and agreed within 3GPP, thus the approach requires the submission of a corresponding change request to 3GPP.

As some of the CCC related information could be relevant only for certain UE (e.g., some dedicated context information, distinct commands for establishment or release of an ON), a dedicated signaling method is also needed. Hence, some modifications to the UL/DL information transfer (for E-UTRAN) or UL/DL direct transfer (for UTRAN) procedures could be an option. These extensions would enable the transfer of CCC data over Iub (UMTS) and Uu (UMTS/LTE) air interfaces to selected peer entities (in contrast to the broadcast of data described above). As the information to be exchanged over CCC is most likely to be collected and stored in a central database, which could be located in the core network (as proposed, e.g., for ANDSF), additional mechanisms enabling delivery of CCC related data to the RNCs/HNBs (for UMTS) and eNBs/HeNBs (for LTE) are necessary. The additional mechanisms could be based on the use of operation and management systems or the extension of the existing radio access network and/or core network protocols (e.g., S1AP, RNSAP).

IEEE 802.11 — The exchange of CCC data between IEEE 802.11 devices can be achieved by exploiting vendor-specific information elements (VSIEs) where CCC information is included as IEs in management frames such as beacons or probes. Alternatively, vendor-specific action (VSA) frames can be exploited, where CCC information is carried using new standalone management frames. The realization of CCC in IEEE 802.11 could be also achieved by exploiting functionalities provided by some of the existing IEEE 802.11 extensions.

IEEE 802.11u, one such extension, has been developed to enable interworking of IEEE 802.11 devices with external networks. In this case, the realization of CCC could be achieved by reuse of the Generic Advertisement Service (GAS), which allows for the exchange of arbitrary information between two non-associated devices using public action frames. In order to enable the transmission of CCC data over GAS, a new Advertisement Protocol ID would need to be introduced. It is worth noting that the usage of IEEE 802.11u may slightly limit the flexibility of the CCC implementation, as GAS requires the request/response exchange scheme (additional overhead in case the exchange of CCC data does not require acknowledgments).

Another IEEE 802.11 extension, which allows realization of CCC, is WiFi Direct, which introduces new features/functions enabling direct communication between devices without the use of an Access Point. Wi-Fi Direct specifies new procedures and provides additional information

In the case of Bluetooth, CCC data provision can be conducted based on the Extended Inquiry Response (EIR) packet, which has been introduced in Bluetooth 2.1 in order to allow better device filtering by providing more information during the inquiry procedure.

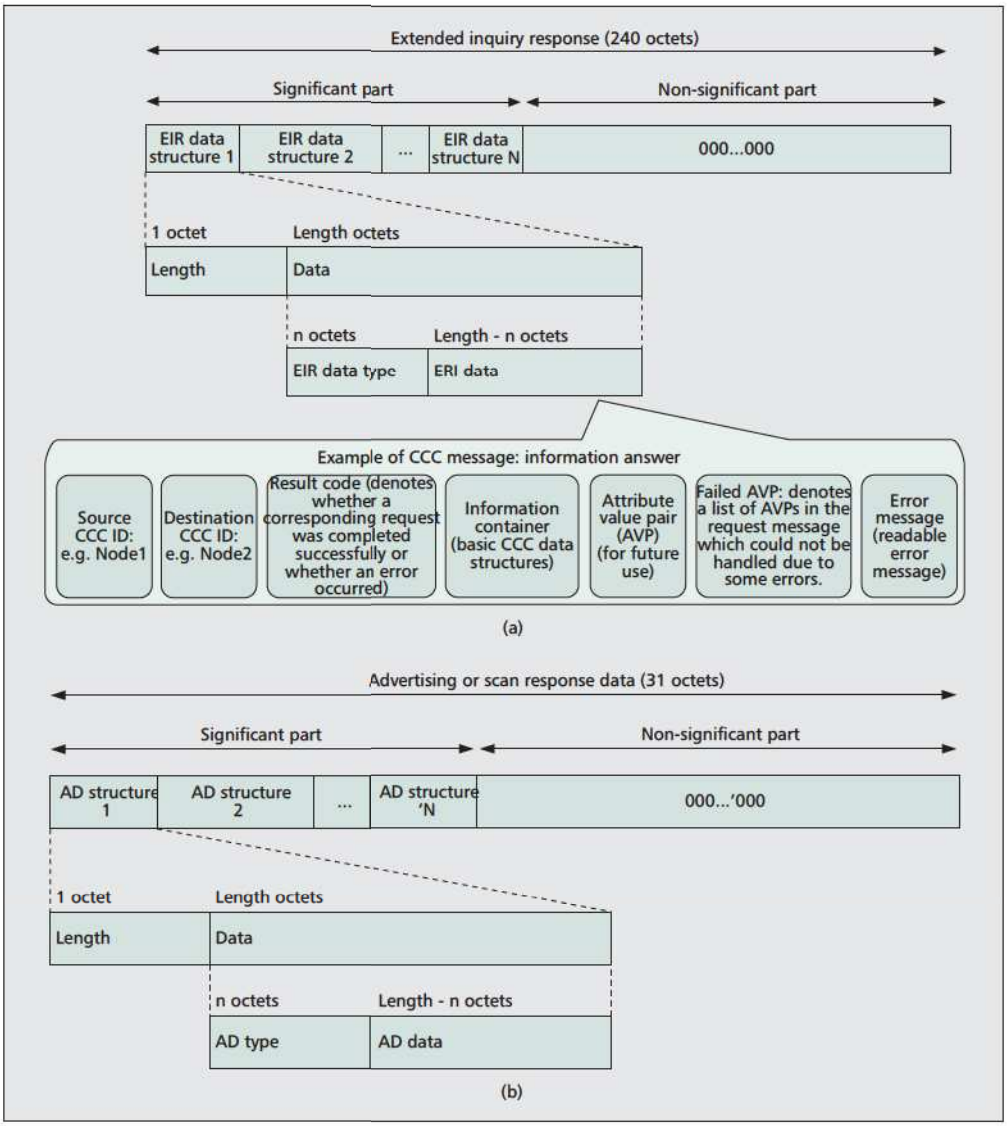

Figure 6. *High-level view of exploitation of Bluetooth for CCC implementation: a) extended inquiry response; b) advertisement and scan response data format [13].*

in IEEE 802.11 MAC frames. The most relevant, for CCC implementation, Wi-Fi Direct features are related to the peer-to-peer discovery and group operation functions. In order to provide additional CCC specific information, further extension of the existing set of peer-to-peer Information Elements could be considered.

WiMedia for Ultra Wideband — The WiMedia distributed medium access control (MAC) as used for ultra wideband (UWB) allows a device to include user-defined data in the form of an application-specific information element in its beacon. Although WiMedia is currently used mostly for implementation of wireless USB or wireless audio-video data streaming, due to increasing interference in the ISM band and the need for larger bandwidth it may be soon employed by a much broader range of applications.

The proposed methods for the exchange of CCC data between WiMedia terminals include the utilization of application-specific information elements or application-specific command frames (presented in Fig. 5). In order to enable their implementation, an additional management entity needs to be introduced. This additional management entity would be responsible for creation and reception of the application specific data content. It is also worth noting here that a possible WiMedia-based CCC implementation could be a hybrid of the two methods, thus allowing for greater flexibility.

Bluetooth — In the case of Bluetooth, CCC data provision can be conducted based on the Extended Inquiry Response (EIR) packet (Fig. 6a), which has been introduced in Bluetooth 2.1 in order to allow better device filtering by providing more information during the inquiry procedure. Another approach could be to use advertisement and scan response packets. It is

CCC implementation options	Layer 1, Layer 2	Layer 3	Layer 4	Protocol	Addressing
IETF Diameter	—	IP	TCP, SCTP	Diameter	IP network
3GPP ANDSF	—	IP	TCP	HTTP, OMA-DM (XML)	IP network
Distributed agents	—	IP	TCP	HTTP, Corba/IIOP	IP network
IEEE 802.21	—	IP	TCP, UDP, SCTP	MIH	IP network and MIH identifier
	IEEE 802 L1, L2	—	—	MIH	L2 address and MIH identifier
3GPP RRC	3GPP L1, L2	RRC	—	RRC	3GPP user equipment identifiers
IEEE 802.11	IEEE 802.11 L1, L2	—	—	802.11, 802.11u and WiFi Direct	L2 address
WiMedia UWB	L1, L2 (UWB)	—	—	ECMA-368	L2 address
Bluetooth	Bluetooth L1, L2	—	—	Bluetooth 2.1	L2 address

Table 1. *Overview of CCC potential implementation options.*

The RAT-independent-based implementation approaches are quite generic and mainly rely on the availability of a certain type of connectivity (i.e., IP connectivity) between CRS nodes.

worth noting that these approaches do not require a connection to be established. In case a connection is established, the Service Discovery Application Profile ((Fig. 6b) could be exploited. The basic idea of the approach is to use service records, which describe a specific service (in this case CCC) to represent the CCC data (e.g., context information, policies), making it accessible to other devices in the neighborhood.

Table 1 provides an overview of the considered options.

Overall Assessment of Potential Implementation Options

The various CCC implementation options outlined in the previous subsections have different advantages and drawbacks. This section provides an overall assessment of the potential implementation options. Table 2 provides a summary of this assessment, depicting how some of the key requirements identified earlier are addressed.

All addressed implementation options meet the requirements for preservation of legacy system operation and compatibility with legacy systems deployment. Furthermore, all addressed implementation options can be exploited for the exchange of information relevant to the setup, maintenance, and termination of ONs. The RAT-independent-based implementation approaches are quite generic and mainly rely on the availability of a certain type of connectivity (i.e., IP connectivity) between CRS nodes. The advantages of the Diameter protocol (as defined in Internet Engineering Task Force (IETF) RFC 3588) are:

- It is an easily extensible protocol to which new building blocks can be added for different applications.
- Relaying as well as proxying of messages are supported.
- It is a well established protocol used, for example, also in 3GPP.

ANDSF is operator-controlled; thus, it is typically used for distributing information related to non-3GPP network nodes that are under the control of the same operator that owns the 3GPP network carrying the ANDSF. While it is in theory possible to extend the ANDSF MO to include CR related parameters, it is of limited usefulness in a multi-operator heterogeneous environment where operators have no roaming agreement and should thus be tailored to the needs of a single operator. JADE and the relevant transport mechanisms have been utilized for implementing the CPC concept in a heterogeneous multi-operator environment (following the information model specified in the standardized IEEE 1900.4 management architecture [14]). The results obtained from the corresponding experimentation showed satisfactory behavior in terms of induced signaling loads (number of delivered bytes, bit rate, overheads imposed by agents' communication) and time delays, which is equivalent to minimal intervention in real network operation. Starting from this work, an extended information flow has been defined in the form of an ontology, and an enhanced platform has been developed, also based on

System requirements	General				Terminals	Protocol		Implementation
Implementation option	Commun. between infrastructure and terminals	Commun. between terminals	System independent	Basic connectivity required	Relaying/ proxying	Information delivery model	Efficiency	Extension of standards required
IETF Diameter	Yes	No	Yes	Yes	Yes	Unicast	Some signaling overhead	Minor
3GPP ANDSF	Yes	No	Yes	Yes	Yes	Unicast	Some signaling overhead	Minor
Distributed agents	Yes	Yes	Yes	Yes	Yes	Unicast, multicast	Some signaling overhead	None
IEEE 802.21	Yes	No	Yes	No	Yes	Unicast, multicast	Low latency	Minor
3GPP RRC	Yes	No	No	No	No	Unicast, broadcast	Low latency	Minor
IEEE 802.11	Yes	Yes	No	No	No	Unicast, broadcast	Low latency	Minor
IEEE 802.11u	Yes	Yes	No	No	No	Unicast, broadcast	Low latency	None
Direct WiFI	No	Yes	No	No	No	Unicast, broadcast	Low latency	Minor
WiMedia UWB	No	Yes	No	No	No	Unicast, broadcast	Low latency	None
Bluetooth	No	Yes	No	No	No	Unicast	Unicast, broadcast	None

Table 2. *Comparison of CCC potential implementation options.*

JADE, with a special focus on openness, scalability, and dynamic extensibility [15]. Indicative results showed that although there is some overhead (due to the agent platform) the overall amount of information exchanged (even in situations where there is large amount of data that needs to be transmitted) is realistic.

The IEEE 802.21 approach covers both L3 and L2 transport options and may have the potential to bridge 3GPP and IEEE wireless systems, while a coexistence with the ANDSF will definitely be required at least for the near- to mid-term. Specifically, MIIS and MIH protocol constitute two relevant RAT independent pieces of the IEEE 802.21 standard to be further considered in a potential implementation of CCC for CRS. In any case, this approach would also require extensions for the transfer of additional context information, for operational control and management procedures for CR networks, as well as for supporting signaling between terminals.

The RAT-dependent-based approaches (e.g., 3GPP RRC, IEEE 802.11, WiMedia, and Bluetooth), on the other hand, are expected to represent low-latency solutions (e.g., no need to establish connectivity beforehand) while they need to be tailored to a specific system. The 3GPP RRC in comparison to RAT-independent provision of cognitive control data has a disadvantage in the fact that the implementation is system-specific; and, as stated in the previous section, any changes needs to be discussed and agreed on within 3GPP. On the other side, the advantages of the approach include fast availability of data due to delivery on the RRC layer and low signaling overhead. The approaches based on IEEE 802.11 (including 802.11u and Direct Wi-Fi), WiMedia and Bluetooth show similar advantages and disadvantages but, unlike 3GPP RRC, they can be used for the exchange of data mainly between user devices (terminals).

From the previous analysis, it seems that none of the proposed options is by itself suitable for enabling a full implementation of the CCC. Therefore, it is expected that the final CCC implementation will be based on a combination of different radio-independent and radio-dependent solutions. Such a combination would eliminate the identified shortcomings of discrete implementation approaches and allow full implementation of CCC supporting efficient exchange of information between user devices as well as between user devices and the network infrastructure. For example, a potential solution could be based on a combination of:

- Bluetooth or Direct WiFi for enabling the exchange of necessary information between terminals
- OMA-DM/ANDSF-based CCC for enabling the realization of the interface between terminals and the infrastructure
- Diameter-based CCC for enabling the exchange of information between elements of the infrastructure (e.g., Base Stations).

Conclusions

This article, taking into account previous and recent work on CCCs, presents technical scenarios in which CCCs can be exploited and outlined a set of derived system requirements. The article provides a high-level view of indicative

CCC messages. Furthermore, the article provides a description of possible CCC implementation options identified based on different existing protocols and systems. More specifically, various options are outlined, including Diameter, ANDSF, distributed agents, 3GPP RRC, IEEE 802.21, IEEE 802.11, WiMedia UWB, and Bluetooth solutions for implementation of the previously mentioned concepts. Examples of exploiting these implementation options for various types of CCC messages are provided. The advantages and drawbacks of the various options are discussed. In general, RAT-independent-based implementation approaches are quite generic and mainly rely on the availability of a certain type of connectivity (i.e. IP connectivity) between CRS nodes. The RAT-dependent-based approaches, on the other hand, are expected to represent low-latency solutions (e.g., no need to establish connectivity beforehand) and need to be tailored to a specific system. It seems that none of the options is by itself suitable for enabling a full implementation of the CCC. Therefore, it is expected that the final CCC implementation will be based on a combination of different radio-independent and radio-dependent solutions. For a more complete assessment of the various CCC implementation options, experimentation work is essential. While some experimentation has been and is being carried out (e.g., [14, 15, 9] respectively), further work in this direction is required to obtain better insight on CCC implementation issues.

It seems that none of the options is by itself suitable for enabling a full implementation of the CCC. Therefore, it is expected that the final CCC implementation will be based on a combination of different radio independent and radio dependent solutions.

Acknowledgment

The authors would like to thank all delegates of the ETSI RRS TC. Discussions with these colleagues were invaluable for setting up this article. This work has been performed in the context of the OneFIT project (Opportunistic Networks and Cognitive Management Systems for Efficient Application Provision in the Future Internet, www.ict-onefit.eu) which is supported by the European Community's Seventh Framework Program (FP7). This article reflects only the authors' views, and the Community is not liable for any use that may be made of the information contained therein.

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