The E3 architecture: Enabling future cellular networks with cognitive and self-x capabilities

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Abstract — Future mobile networks are expected to be complex heterogeneous systems. On the one hand this will enable users to take advantage of a number of different access technologies. On the other hand this will seriously affect network management procedures since more extensive operations and decisions will have to be dealt with. To tackle these challenges a number of new dynamic mechanisms need to be designed. It is imperative that certain network management tasks have to be performed without human intervention to reduce the OPEX costs and have faster responses in different events. To achieve this goal, the introduction of self-x functionalities, combined with cognitive mechanisms and the ability to reconfigure network entities and terminals is required. Moreover, the introduction of a new pilot channel needs to be considered to assist the terminals selecting the most suitable radio access technology according to their needs. We present the functional architecture of an evolved network that was designed in the context of the EU funded IP project “E³ – End to End Efficiency”. This architecture aims to enhance existing procedures usually performed in traditional Operation & Maintenance systems (e.g., spectrum management, network planning, configuration actions etc). We explain the rational of our design and provide specific examples to illustrate the role of the different functional entities and their interfaces. A considerable part of this architecture has been recently approved as a feasibility study by the ETSI Committee Reconfigurable Radio System (RRS).

Keywords: Network management, wireless and mobile networks, distributed management, autonomic and self management, policy based management

I. INTRODUCTION

Future mobile networks present a number of challenges regarding functions that are not present in legacy homogeneous systems. These networks will be composed of a number of different Radio Access Technologies (RATs). This will allow users to be connected through more than one access network. However, the existence of different access opportunities calls for mechanisms to inform the terminals on existing access networks and even provide them with additional information (e.g., radio resource usage policies, current status of specific spectrum bands, location of protocols to be used during a reconfiguration action, etc). Moreover, there is a need for the network components and the terminals to determine automatically the radio conditions and the radio link quality from different access technologies. Based solely on the current technologies a terminal would be forced to perform a large band scanning or connect to one of the existing access networks and then collect the necessary information. These solutions however introduce considerable latency and affect the battery lifetime of the terminals. Additionally, the network components (e.g., the base stations) would need to be configured centrally as is done today. This implies that they would be incapable to react rapidly and dynamically every time an event (e.g., increased level of interference) calls
for a new configuration of their operation. To tackle such issues we introduce three new enablers. The first one is called Cognitive Pilot Channel (CPC) that will constantly collect information from the corresponding network components and broadcast it to the terminals through a new logical channel. The second enabler is called Cognitive Control Radio (CCR) that is an out of band peer-to-peer communication radio between network nodes to exchange information for the radio status in the unlicensed bands. The third enabler is called Spectrum Sensing (SS) and is used to collect information from the network nodes by sensing the current status of the radio environment in their geographical area.

Another important challenge is to modify the well established network management mechanisms designed for homogeneous networks to serve the needs of future mobile networks. The design of the new mechanisms is imperative since the co-existence of different technologies calls for new solutions for network planning, spectrum management, detection of malfunctions and their actions needed for their repair. This implies that the appropriate information needs to be collected from the different systems. Thus, these mechanisms will base their operation on the context information collected by the three enablers (i.e., CPC, CCR and SS) as well as the network components and the terminals. This information is processed and evaluated by intelligent modules that fine tune the overall performance of the network in an automated and dynamic way, avoiding as much as possible the need for human intervention.

To improve the Operation and Maintenance (O&M) functions, new approaches are needed and key enabling technologies are required. One such enabler is the use of cognitive radio technology. Cognitive radio is actually the capability of a wireless network device to be aware of its operational environment and to be able to adapt intelligently its operational parameters and protocols according to this knowledge in new situations in order to achieve predefined objectives (e.g. more efficient utilization of spectrum). Cognition can include mechanisms to learn from previous decisions to improve the performance of actions to be executed in the future. Using this technology, the devices are aware of the network context and can take complex decisions.

Another enabling technology is the introduction of a certain level of autonomic operations by the network components. The goal is to reduce the complexity of O&M procedures, moving from legacy centralized systems to more dynamic and distributed systems. This autonomic functionality enables the realization of several functions such as self-management, self-optimization, self-monitoring, self-repair, and self-protection. Standardization bodies are already pushing towards the notion of self-organizing networks (SON).

The aforementioned technologies are applied in reconfigurable components. Reconfigurability enables terminals to dynamically modify their operation mode. This capability may span through all the layers of the protocol stack from modulation techniques to error control mechanisms, routing protocols, transport layer mechanisms, video codecs etc.

The goal of the European funded research project E³ (End-to-End Efficiency) is to use these three enabling technologies (i.e., cognition, autonomicity and reconfigurability) and combine them with the use of a CPC as the basis to build innovative and enhanced architectures and mechanisms. The main idea is to blend cognition with autonomic functionalities and use reconfigurable systems to achieve highly intelligent and adaptable network components and mobile terminals. The outcome of this process is a novel architecture that deals with future networks requirements. The importance of his contribution is further justified by the fact that a considerable part of the proposed architecture has been approved as a feasibility study by the ETSI Committee Reconfigurable Radio System (RRS) and has recently received the mandate to proceed with the next steps towards its standardisation within ETSI.

To design the architecture we followed a specific methodology starting from the definition of a large number of usage scenarios and designed an information model that depicted the plethora of parameters that need to be considered in such an environment. From these we extracted specific operation requirements that were mapped into elementary operation functions. The correlated functions were grouped into functional blocks that were mapped into existing network components. Methods and algorithms that were designed as
firm candidates for the defined functional blocks of the architecture were also implemented and tested within
E3 project, thus giving evidence on the feasibility of our design. Finally, we also identified key issues for
assessing the functionality of cognitive and autonomic components.

The structure of this paper is as follows; in section II we provide information on related activities in this
area. In such a complex and heterogeneous network environment, an information model is required to
illustrate new concepts and the information to be considered, collected and processed. E3’s information
model is presented in section III. In this section we also present the functional entities that realize the desired
network operation and their mapping to existing network components. Section IV discusses the cognitive and
self-x capabilities of the E3’s functional entities. Section V presents how the functional entities interoperate
during the execution of specific network scenarios. Section VI discusses a very interesting issue that is how
to assess the performance of cognitive systems. We conclude the paper and sketch future research directions
in section VII.

II. RELATED WORK

During the past years, strong research effort has been spent in the cooperation among heterogeneous wireless
standards VII, mostly in order to effectively accommodate demand via exploitation of the situated
infrastructure. In the sequel, research has been placed on the reconfiguration ability of terminals and network
elements with assistance of Software Defined Radio Technology. The EU’s 6th Framework Program for
Research and Technological Development enriched and complemented scientific work, relevant to the
cooperation and reconfiguration of legacy standards. Research in the field of interworking of diverse systems
has been mainly targeted at gathering inputs from numerous entities within a network and taking decisions
appropriate for performance optimisation VII. Apart from this, related research areas have included
reconfigurable radio resource management VII, as well as spectrum management VII and radio enablers, in a multi-radio environment. These have been achieved by a) monitoring and analysing the
statistical performance and the associated QoS levels provided by the network elements, b) inter-working
with service provider mechanisms, c) performing dynamic network planning as a result of resource
management strategies, and d) introducing in the network new radio enablers providing information on
available RATs, operators, frequencies allocated to RATs, etc. in a specific area. Equipment related research
has focused on the cooperative operation among terminals served through RATs [15], and on reconfigurable
equipment, i.e. capable of performing modifications to the terminal online and over the air, in order to adapt
to the environment.

However, the accumulation of the wireless landscape with continuously novel standards and features and the
augmented requirements of a variety of new advanced services/applications render this situation prohibitively
complex. The introduction of cognitive radio VII and the adoption of cognitive capabilities to network
systems and terminals seem to be an efficacious response to this complexity VII. In the framework of
cognitive wireless networks, important advancements have been effectuated by projects, independent
research in universities and institutes and standardization bodies, focusing on different fields such as
management architecture, algorithms, protocols, flexible spectrum management and business models.
Concerning cognitive network architectures, there are several approaches with different goals, level of
cognition and actions to different layers of the protocol stack. Among these approaches, the Personal Router
project VII proposed customized wireless services and user satisfaction by using a cognitive agent (named
personal router) that selects the suitable wireless network to user’s preferences, Mahonen et al. in VII
proposed a cognitive resource manager architecture for resource usage optimization, which enables
reconfiguration of parameters in all layers of the protocol stack in any entity that participate in resource
management, and Sutton et al in VII proposed a reconfigurable platform for optimized resource management
that exploits device level cognition and consists of reconfigurable wireless nodes.
Furthermore, there are several research activities in the area of self-x functionality, including initial support of primary self-capabilities, such as the self-configuration and optimisation on radio networks dealing both with the user device and the infrastructure equipment side VII. Besides, standardization bodies like 3GPP are also working on self-configuring and self-optimizing networks VII. Necessary prerequisites for implementation of self-x capabilities are the learning capability and knowledge accumulation. In this context, knowledge representation VII and mechanisms/techniques for knowledge derivation VII have concentrated research interest with different approaches.

Moreover, architecture related state of the art comprises the results from several European funded projects VII, the architecture developed in 3GPP for the system architecture evolution VII, the report on the functional architecture for the management and control of reconfigurable radio systems developed in the ETSI VII and the standards produced by the IEEE Standards Coordinating Committee 41 on Dynamic Spectrum Access Networks like the 1900.4 standard VII.

Despite the described evolution, we identified the lack of an integrated, scalable and easily expandable architecture for future mobile networks that will successfully tackle the difficulties and challenges in technological, regulatory and business domains altogether. This was exactly the focus of E3, which utilises the cognitive capability, learning functionality and knowledge management of network elements and terminals and the powered infrastructures, in order to achieve end-to-end efficiency VII. In this context, E3 conducted research on business models, functional/system architecture, collaborative optimisation techniques, autonomic elements, cognition enablers, prototyping, standardisation and regulation.

E3 has progressed the current “state of the art” in business domain, by developing a unified model describing the business and technical ecosystem, and in technological domain, by creating new and developing existent functionalities and mechanisms in radio resource management, self-organizing, flexible spectrum management, cognition enablers and reconfiguration management. Particularly, E3 has developed i) decision-making and optimisation schemes targeting on collaborative radio resource management, dynamic spectrum access and reactive and proactive handling of problematic situations, simultaneously with autonomous functions/algorithms; ii) mechanisms for context acquisition; iii) radio enablers for collaborative/autonomous optimisation and reconfiguration; iv) mechanisms for derivation of policies for spectrum assignment in the regulatory framework; v) the necessary business models. Finally, E3 has defined an overall system architecture (functional architecture with accrued interfaces and information model) targeting to improvement of radio resources utilisation and decrement of the effort required for deployment and operation of reconfigurable Radio Access Networks (RANs).

III. THE E3 ARCHITECTURE

In the section we provide a description of the E3 information model, the functional architecture as well as the mapping of the functional blocks into the LTE/SAE’s architecture network components. The information model provides some insight on the new concepts introduced in a cognitive and self-x network environment. It also presents some of the information that needs to be taken into consideration by the functional entities. These entities have been derived following a methodology where scenarios and requirements have been analyzed and related functionalities have been grouped into functional blocks. The following subsections present these functional blocks as well as their mapping into existing network components.

III.I The E3 Information Model
An information model is a conceptualisation that includes the entities’ properties and operations and the identified relationships among the entities. It is independent of any specific repository, application, protocol and platform VII. As stated in VII it can be defined using a formal language. More specifically, the Unified Model Language (UML) VII class diagrams can be used for the specification of an information model to represent the involved entities and the relationships that have been defined between them in a standard graphical way.

The E3 managed environment is composed by the B3G/4G telecommunication environment which is mainly characterised of (i) a plethora of user devices, with different capabilities and configurations, being operated in a dynamic and reconfigurable mode, (ii) a vast number of mobile applications that are developed and provided from different vendors and with different requirements, and, (iii) high availability of different types of networks (e.g. WLAN, 3G, UMTS, WiMAX etc). The information model captures the information that needs to be collected, processed and exchanged inside the network. It also introduces new concepts that have meaning in cognitive and self-x enabled environment.

In such an environment the key concepts and entities that form the abstraction in question is ever growing up; additionally, the elementary information types, context and policy information are also mixing their boundaries. A context is usually referred to as “any information that can be used to characterise the situation of an entity (a person, place, or object) that is considered relevant to the interactions among all the involved actors within the managed system. On the other hand, the concept of “Policy” stands for the counterpart of the contextual information that is required to model the behaviour of the entities within a managed environment. Context conceptualizes entities, actors and interactions; policies, are used for abstracting specific actors goals, and objectives in various levels, business, technical and administrative. In VII, the term “Policy” is defined as (i) a definite goal, course or method of action to guide and determine present and future decisions, and, (ii) a set of rules to administer, manage, and control access to network resources.

In E3, a complete list of information elements has been derived, in different levels of detail, based on the project’s technical use cases. Such use cases captures features and functionality for cognitive radio systems including (i) self-optimisation in heterogeneous networks, (ii) self-optimisation in single-RAT networks, (iii) self-maintenance/self-healing, (iv) self-(re-) configuration, (v) operation of autonomous terminals, and, (vi) flexible spectrum management. In this sense, the key concepts that compose the high level of information abstraction include: the Network Operator, The User that utilises a number of terminals for service provision/consumption purposes, the terminals, the RANs and the deployed RATs, the base stations/access points, the cells, the ad-hoc networks, the services and the hotspots.

A UML model has been developed for each of the E3 information concepts (see Figure 1) which models such concepts through classes and attributes in various abstraction levels. The IEEE P1900.4 and the 3GPP ANDSF served as reference information models; the comparison between the E3 concept and the reference models highlight potential gaps that are fulfilled by the E3 information model. In the following paragraphs
indicative E3 information concepts are presented together with the comparison to the standardized reference models.

1) User Concept

The User concept includes the User profile that is composed by the home and the work profile of a user. Moreover, the model incorporated information about the user preferences, the user requirements and the user experience as outlined by the respective classes. The user subscription provides information about the user's subscriptions to network and application service and is associated with the user requirements and the running service that abstracts any service that has been deployed in a user's platform. A comparison of the information models for a user between E3, P1900.4 and the 3GPP ANDSF is shown in Table 1 (the symbol √ means that the specification group incorporates the related information while the symbol X has the opposite meaning. The first column contains the incorporated information in the E3’s information model):

<table>
<thead>
<tr>
<th>User</th>
<th>E3</th>
<th>P1900.4</th>
<th>ANDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Profile</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Home Profile</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work Profile</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Preferences</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Data Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Experience</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of QoS</td>
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<td></td>
<td></td>
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<tr>
<td>Running Service</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subscribed Service</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Service Type</td>
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<td></td>
<td></td>
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</tbody>
</table>

Table 1: User Information Model Comparison.

2) RAN and RAT Concepts

Within the E3 context the RAN concept is related to the RAT; in P1900.4 such concepts have been incorporated through the Base Station and Cell related classes. For example, the listSupportedRadioInterfaces attribute is included in the BaseStationCapabilities class. It has to be noted that the term “Base Station” in the scope of P1900.4 is used to refer to any radio node on the network side; this will be detailed in the Base Station Model. A set of identified RAN related measurements that are listed in the table below can be considered as already incorporated in the P1900.4. For example, the Radio Load can be considered as an extension to the Cell Measurements class. A comparison of the information models for a RAN between E3, P1900.4 and the 3GPP ANDSF is shown in Table 2:

<table>
<thead>
<tr>
<th>Radio Access Network (RAN)</th>
<th>E3</th>
<th>P1900.4</th>
<th>ANDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAT Type</td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>RAT Policies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAN Status</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing Load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport Load</td>
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<td></td>
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</tbody>
</table>

Table 2: RAN Information Model Comparison
The concept of the RAT Protocol is included in the E³ context. At the same time, such concept is not incorporated in the P1900.4 information model. A *RATProtocol* class can be added as extending the *BaseStationCapabilities* in order for the RAT Protocol to be abstracted in the model. Such class will aggregate the concepts of the Protocol Component, Protocol Metadata and Protocol Configuration as member classes whereas the corresponding attributes shall be defined. This is quite important for E³ as the concept of reconfigurable protocol has been a subject of the project work; additionally, such concept has been included in several use cases. In this sense, the protocol related information come to close any gaps in the standardized information models regarding reconfigurable protocols. A comparison of the information models for a radio access technology between E³, P1900.4 and the 3GPP ANDSF is shown in Table 3:

<table>
<thead>
<tr>
<th>Radio Access Technology (RAT)</th>
<th>E³</th>
<th>P1900.4</th>
<th>ANDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAT Protocol</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Protocol Component</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Protocol Metadata</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Protocol Configuration</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
<tr>
<td>Assigned Spectrum</td>
<td>☑</td>
<td>☑</td>
<td>☑</td>
</tr>
</tbody>
</table>

Table 3: RAT Information Model Comparison.

3) Policy Modelling

In the scope of E³, policies are abstracting specific actors’ goals, and objectives in various levels, business, technical and administrative. A number of different types of policies are incorporated in the E³ scope, such policies derive from the involved actors strategies and objectives (i.e. the Network Operator, the User, etc) and target the system entities behaviour in a specific technical area (i.e. Flexible Spectrum Management, RAT Selection, etc.). The different types of policies that have been identified in the context of E³ are presented in the following list:

- Dynamic Spectrum Access (DSA) Policy is derived by the operator taking into account corresponding regulatory rules for establishing the frequency ranges of the RATs,
- Radio Resource Assignment (RRA) Policy is derived by the network and conveyed to the terminals; such policy gives straight indication to user terminals regarding radio resource assignment,
- Mobile Terminal Assignment (MTA) Policy is derived by the network and communicated to the network elements (infrastructure manager, Base Station) for optimal terminal distribution between different RANs targeting resource usage optimization,
- RAT Selection Policy is derived by the network and communicated to the user terminals for the access selection procedure,
- Energy Saving Policy is derived by the network and conveyed to infrastructure management in order to drive the network elements behaviour for energy saving. For example, decision about switching on/off cells,
- Handover Policy is derived and conveyed from the network to the terminal in order to assist the terminal decision regarding an inter-RAT handover,
- SON Policy is derived and exchanged among network elements and user terminals in order to define the most efficient organization structure and its behaviour.
Table 4 presents a comparison between the $E^3$ Policy Types and the corresponding work in the P1900.4 and the ANDSF. It must be noted however that such comparison has been done based on different viewpoints. P1900.4 information incorporates specific policy types, so the comparison has been elaborated based on the policy types. However, ANDSF doesn’t deal with specific policy types but provides mainly generic policy model attributes that can be incorporated in every policy type, such as the priorities of the various rules which compose a policy, the validity area of a policy and the time interval during which a specific policy is valid and/or applicable. In this sense, a couple of $E^3$ policy types are mapped to P1900.4 whilst ANDSF policy modelling is linked to every $E^3$ policy type.

Table 4: Policy Model Comparison.

<table>
<thead>
<tr>
<th>Policies</th>
<th>$E^3$</th>
<th>P1900.4</th>
<th>ANDSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Spectrum Access Policy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Resource Assignment Policy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile Terminal Assignment Policy</td>
<td>□</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAT Selection Policy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Saving Policy</td>
<td>□</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handover Policy</td>
<td>□</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SON Policy</td>
<td>□</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These policy concepts are modelled as part of the $E^3$ Information Model. Specifically, the identified policy types are associated to $E^3$ concepts i.e. actors, both technical and business, such as the Network Operator, the User, the Base Station, and the Terminal. For example:

- The DSA Policy and the RRA Policy are associated to the corresponding Regulatory Rules, the Operator and the RAT; this means that this type of policies is applied to the RATs, and is derived by the Operator taking into the regulatory rules that are applicable in the area. The Operator derives its policies based also on its business strategies,

- The MTA Policy and the RAT Selection Policy is derived based on operator’s business strategies and are applied to Base Stations and Terminals respectively, whereas the SON Policy is applied to both Terminals and Base Stations.

III.2 Functional Architecture

The functional architecture of E3 consists of a number of distinct functional blocks. These blocks have been proposed through a well defined methodology. As mentioned earlier we commenced by defining of a large number of use cases that captured the key concepts of reconfigurability as well as autonomic and cognitive capabilities. Next, the key functionalities implied by the use cases have been identified and grouped according to their similarity thus, resulting in the definition of functional blocks. To achieve this, the use of the information model has proven very helpful. Finally, interfaces between the functional blocks have been identified and related messages have been defined.
Figure 2: Functional Architecture

Figure 2 presents the functional architecture for the case where a single operator is assumed. The figure presents the functional blocks of the terminal and the network side.

On the network side the Dynamic Spectrum Management (DSM) VII provides the mid- and long-term management of the spectrum (e.g. in the order of hours, days) for the different radio systems. The DSM provides knowledge on the policies for the spectrum assignment, which must include the regulatory framework for the spectrum usage.

The Dynamic Self-Organising Network Planning and Management (DSNPM) VII provides the medium and long term decision upon the reconfiguration actions of a network segment, by considering certain input information, and by applying optimization functionality, enhanced with learning attributes. The DSNPM for example decides on the optimal configuration of a Flexible Base Station (FBS). Such (re-)configuration decisions are then given to the RCM which is then responsible for the execution of the reconfigurations.

The Joint Radio Resource Management (JRRM) VII performs the joint management of radio resources that might belong to heterogeneous RATs. It selects the best radio access (“Access Selection”) for a given user based on the requested QoS (bandwidth, max. delay, real-time/non real-time), radio conditions (e.g. abstracted signal strength/quality, available bandwidth), access network conditions (e.g. cell capacity, current cell load), user preferences, and network policies. JRRM also provides neighbourhood information for the efficient discovery of available accesses.

The Self-x for RANs (Self-x for RAN) VII enables the automation of operational tasks. It targets the self-organising functionalities for the RAN, mainly providing short to medium term decisions. It focuses on radio access technology specific operator use cases. This functional block cooperates with the DSNPM (regarding Key Performance Indicators – KPIs and policies), with the JRRM (regarding the execution of Self-x for RAN decisions, provision of measurements) and with the RCM (regarding the various reconfiguration control functions). On the terminal side the block is used mainly to support the self-x operations of the network components (e.g., collecting statistical information). In order to ensure simplicity in our architecture we decided that its communication with its counterpart entity on the network side should be done through JRRM avoiding an excessive and unnecessary number of interfaces between the terminal and the network side.

The Reconfiguration Control Module (RCM) is mainly responsible for the execution of the reconfiguration of a terminal or a base station, following the directives provided by the other building blocks, typically the DSNPM, the Self-x for RAN and the JRRM. It is required in reconfigurable terminals, base stations, and
optionally other reconfigurable network elements (e.g. mobility anchors) so as to enforce and realize their adaptation to the current context.

All these functional blocks follow a cognition loop where a component is continuously monitoring a set of variables related to the network and/or terminal conditions and performance. If an event occurs (e.g., there are no longer any available resources for a BS, a new radio access technology is detected by a mobile terminal, etc.), then the component evaluates the collected data and takes a decision to execute an appropriate action. Then, this action is performed and the results from such an operation are recorded and evaluated in order to optimize any future related decisions.

To support the operations of the E3 functional blocks we have identified three “cognition enablers” that assist in the phase of collecting information from the network environment.

Terminals are informed by a logical channel, called the Cognitive Pilot Channel (CPC) VII, about a number of parameters that are needed by the terminals to operate more efficiently, e.g. the available radio access technologies in a geographical area, the frequencies that these technologies are using, etc.

The second enabler is called Cognitive Control Radio (CCR) VII and is an out-band peer-to-peer communication radio between heterogeneous network nodes (e.g. between terminals or between an access network and associated terminals) for the exchange of cognition related information. It operates on a known frequency. It is meant for use in unlicensed bands, where cognitive mobile terminals may operate. Note that this “cognitive band” may contain legacy primary users. CCR is like a narrowband ad-hoc wireless LAN complemented with multi-hop networking. Consequently, the PHY and MAC layers designs should focus on the minimization of power consumption.

Finally, the third enabler, called Spectrum Sensing (SS) VII, focuses on gaining knowledge related to the available radio systems by sensing, the characterisation of radio conditions and the radio link quality estimation. In cooperation with the CCR or the CPC, SS information can be distributed between different nodes. These three enablers are not depicted in Figure 2 since their functionality is considered to be implemented by lower layer protocols.
In Figure 3, we present the functional architecture for the case of multi-operator environment. It has to be noted that dependent on the level of co-operation between the operators, one, two or all three of these inter-network interfaces will be used. The SS-Interface can be used for the negotiation related to spectrum usage between operators. The MM-Interface can be used for the exchange of information on the network configuration in order to avoid or reduce interference between the networks. The JJ-NN interface can be used for the handover of terminals between the networks, e.g. for load balancing.

Note that a terminal is typically connected to one network, but as indicated with the dashed line in Figure 3, a terminal may also be connected with two or more operator networks at the same time, e.g. receiving one service via the first network while another service is using the connection to the second network. During a handover between the networks, the terminal may also use both JJ-TN interfaces to both operator networks.

Furthermore, as shown in Figure 4, ad-hoc and multi-hop scenarios are also supported by the FA of E³. Instead of a JRRM building block this scenario contains the AEM building block VIVIVIV which provides similar functions to JRRM, but as a conceptual difference to JRRM the AEM works more autonomously and does not communicate with the RAN. Instead, it communicates with other devices directly using the AA-interface.
Figure 4: Functional Architecture (ad-hoc or multi-hop case)

III.3 Mapping to LTE/SAE

The system consists of the UE connected to one or more evolved RANs, and evolved RANs connected to one or more evolved packet core networks, with core networks providing connectivity to external Packet Data Networks (PDNs). The evolved packet core works in conjunction with a) legacy 3GPP access systems (2G/3G) through the legacy UMTS core network, b) trusted non-3GPP IP access networks, and c) WLAN access networks through the evolved packet data gateway. The evolved 3GPP system also consists of the Home Subscriber Server and 3GPP service-stratum systems/functions such as the Policy and Charging Rule Function (PCRF), the Application Function, the Broadcast/Multicast Service Centre (BM-SC), and the IP Multimedia Subsystem.

The evolved RAN consists of a number of evolved Node-B’s (eNBs), whereas the evolved packet core consists of a) the Mobility Management Entity (MME), b) the Serving Gateway (S-GW), and c) the PDN Gateway (P-GW).

In this section we map of the previously defined functional blocks to the LTE – SAE architecture. In Figure 5 we illustrate the placement of the Functional Blocks in the network components. As it can be seen, RCM is placed in all the reconfigurable devices (i.e., the mobile device, the FBS, SAE Serving Gateway and the PDN Gateway as well as in ePDG. The design choice for this is that these devices should be able to execute the reconfiguration actions to support decisions made by other Functional Blocks (e.g., decision on RAT selection and reconfiguration of protocol stack by JRRM, a new planning scheme from DSNPM, or the decision for reconfiguration of a FBS by Self-x for RAN to cope with the network failure of a neighbouring FBS).

The CPC information to be advertised will be provided by the JRRM and towards the base stations sending out the CPC information. Additionally, CPC functionality is also located in the terminal, e.g. to collect the broadcasted CPC information or to send CPC requests on the uplink in order to receive network specific information (e.g., the existence of available RATs in an area).

Spectrum Sensing (SS) is implemented in FSB and UE. It is able to perform wideband and narrow band sensing. It also processes the sensing results for collaborative spectrum sensing and changes the format of the results suitable for DSNPM.
JRRM is a core functional block which is distributed between the terminal and the network. On the terminal side, the JRRM-TE makes measurements on link performance as well as idle state access selection. In the connected state, the access selection is made together with the JRRM on network side. There, different options exist where the JRRM can be located. JRRM functionality is typically located in the base stations (e.g. eNodeB) while additional parts of its functionality - as discussed in 3GPP under the term ANDSF - can be located more centrally.

Self-x for RAN is located in the access network components (e.g. FBS, HNB), in the core network (MME) and in the O&M. As Self-x for RAN targets the self-organising functionalities for the RAN, it enables the use of autonomicity of network access components for cases like the optimisation of handover parameters, self healing actions in cases of cell outage, and load balancing. Self-x for RAN cooperates with DSNPM (on KPIs and policies), with JRRM (execution of Self-x for RAN decisions, provision of measurements) and with the RCM that executes decisions taken by Self-x for RAN.

DSNPM functionalities are placed in O&M, in EPC (MME) and in evolved RAN (FBS). Execution of for example specific Policy Management Functionalities might be executed by PCRF and/or HSS.
The DSM function is located in the O&M, where DSM provides a framework of operator policies and legal constraints on how the spectrum can be used in the network. The final decision on which spectrum to be used in a base station is then made inside the RAN (FBS) mainly by DSNPM.

These functional blocks should be realized as an extended NAS signalling in both the UE and the MME. Additional functionality is required in above RRC in eNodeB and S1-AP. Moreover, S1-AP in eNodeB and MME should also be extended. Finally, for the support of DSNPM, additional functionality needs to be added on top of GTP-C in S-GW and P-GW.

For the case of mesh networks (i.e. use of IEEE 802.11) E3 specifies the use of two functional blocks namely, AEM and CCR. The Cognitive Control Radio is an out-band peer-to-peer communication radio between heterogeneous network nodes for the exchange of cognition related information. The information transmitted through CCR includes:

- Messages to assist a newly deployed node to find the frequency of its network.
- In case a network has a low node density, the co-located networks share their spectrum sensing results and their transmit/receive parameters over the CCR. In this way each network will get improved spectral context information.
- Negotiation messages about the spectrum use. The aim is to avoid conflicting spectrum use decisions through negotiation and improve fairness.

The purpose of AEM is to achieve optimal device configuration and to decide on the best ad-hoc means of communication. Towards this end it collects information from CCR and asks from RCM to execute its decisions. It also communicates with JRRM for the cases where the UE is connected within a mesh environment and to an infrastructure based network simultaneously. Through JRRM, AEM collects policy and context information. AEM can also notify JRRM to perform infrastructure based RAT selection if this is required for an optimum device configuration. AEM is the main entity involved in re-organization and new formation of mesh networks to achieve an optimum performance (e.g., battery consumption minimization).

The functionality of both AEM and CCR can be implemented as application layer protocols on a typical TCP/IP node. In Figure 6 we present a mapping of the E3 entities in the case of a mesh network operation.

![Figure 6: Mapping of functional blocks in a mesh based environment](image-url)
The requirements of future mobile networks, accrued from their complex operational environment, necessitate cognition capability of the functional blocks of the emerged architecture, facilitating by the three cognition enablers (CPC, CCR and SS) presented in the previous section.

Cognitive capability, which enables systems to “determine their behaviour, in a reactive or proactive manner, based on the external stimuli (environment aspects), as well as their goals, principles, capabilities, experience and knowledge” VII, constitute the determinant element of self-x functionalities that characterize E3 architecture. The level of cognition, the operating self-x functionalities (self-configuration, self-planning, self-optimization, self-managing, self-healing VII) as well as the realization components of each self-x functionality for the functional blocks, depend on the exact role, the responsibilities and the related functions of each functional block.

Key factor of the cognitive operation is the learning capability that enables the acquisition and accumulation of knowledge via proper processes. The generic self-x mechanism is depicted in figure 7. This self–x mechanism is present in the following functional entities; a) the AEM when a mobile terminal is operating in an ad-hoc mode, b) the DSNPM to optimize the core network and c) the self-x (for RAN) to optimize the operation of the RANs.

Figure 7: Generic Self-x mechanism

In the framework of future mobile networks, in the previous definition for the cognitive capability, “goals & principles” are integrated into term “policies” and the “capabilities” are illustrated in term “profiles”. More specifically:
Policies are the rules which comprise the framework of the operation of each functional block involving self management. These rules illustrate the strategy of the network operator (specialized for the network elements that implement respective operations of the functional blocks) or the personal strategy of each user (for the terminal devices), as well as constraints posed by relevant official organizations. Policy management consists of all the procedures and actions which are related with the derivation, the storage, the supply to the corresponding functions and the control of the policies.

Context encompasses the information which is related to the status of the managed entities (network elements and/or terminal devices) and their close environment (e.g. interference condition, propagation environment). Accordingly, Context management consists of all the procedures and actions which are related to the procession of the collected information from different sources and functional blocks, the extraction of combined information in proper format and its storage and supply to the corresponding functions, according to the emerged event, in definite time.

Profiles incorporate information about the capabilities and the alternative configurations of the managed entities, statistical data derived from their behaviour, user’s preferences, as well as special characteristics of elements that are related with their operations, e.g. acceptable QoS level for each service.

Learning Capabilities embrace the processes which exploit all the available information (extracted from context and profiles information) combined with the results of Decision Making, in order to derive new knowledge. Learning capabilities’ processes apply different learning techniques, according to the operative functionality, such as cluster analysis techniques, classification techniques and reinforcement learning techniques. Knowledge management comprises all the procedures, which based on the knowledge acquired via the Learning Capabilities enhance the operation of Decision Making. Knowledge management utilizes different methods/algorithms such as analytic optimization algorithms, combinational optimization algorithms (Genetic algorithms, Tabu search, Greedy search, Simulated Annealing, Particle Swarm Optimization), Neural Networks.

Decision Making is the process which determines the proper actions according to the specific self-x functionality, based on context, profiles, policies and knowledge. The Decision Making process is effectuated via different methods according to the specific goal and functionality. For example, load balancing in neighbouring cells in a single-RAT cell cluster is implemented based on rule-based algorithm.

In order to clarify the how the functional entities enabled with self-x capabilities interoperate using the required information as defined in section III consider the following two examples. In the first example, traffic congestion occurs and the corresponding self-x functionality (self-managing VII) of the relevant functional block (DSNPM) is activated to confront the situation via proper actions. Namely, context information (i.e., RAN Status in the information model) gathered from the corresponding functional blocks (JRRM and DSNPM) identify traffic congestion in a specific geographical region. This information is processed by the Context Management functionality of DSNPM, is forwarded to the Decision Making component of DSNPM to perform suitable actions. At the same time information from the profiles of the FBSs (i.e., RAT type in the information model) in the specific geographical region is forwarded to Decision Making component. Corresponding context and profiles information is then forwarded to Knowledge Management. Knowledge Management contrasts the current “state” with previously seen ones, and in case specific similarity criteria are satisfied, it informs the Decision Making component to execute the appropriate decisions/solutions/actions. The comparison between current and previous states can be performed by using context matching algorithms VII, which aim at finding the closest reference context to the new context. The decision may consist of new configuration (concerning operated RAT and frequency) of FBSs in the specific area, allocation of traffic load to FBSs and allocation of QoS levels to services. Decision Making component controls if the proposed solution can be implemented. If it is feasible,
it forwards the decision to the suitable functional blocks (e.g., the RCM for reconfiguration of a FBS) and if it is not, it proceeds to proper processes/algorithms in order to find the optimized solution. The decisions are in the framework which is determined by the relevant policies for each specific occasion.

As an additional example consider the case where a terminal may choose from different radio access technologies for one of its services. The self-x functionality of AEM is triggered and the relevant context information (e.g. operating RAT, available frequencies/resources as described in the RAT Type and RAN Status in the information model) is collected from CPC and or CCR and JRRM. This information is processed from Context Management module of AEM. Then it is passed to the Decision Making component together with the user’s and terminal’s profile information (as defined in the User and Terminal concepts of the information model). The decision is taken considering related policies from Policy Management (e.g. rules/policies of regulators for the permitted RATs per frequency band and user’s strategy, i.e., the RAT selection policy and the user preferences in the information model), and terminal’s behavior in similar conditions obtained from Knowledge Management. If the “possible solution” as suggested from the Knowledge Management component is satisfactory, the Decision Making entity adopts it. If it is not, Decision Making entity decides which access network to select via an optimization procedure that evaluates all available information using utility based functions, fuzzy-neural mechanisms or game theory fundamentals.

V. EXAMPLES OF THE ENHANCED E3 NETWORK MANAGEMENT MECHANISMS

In this section we present additional examples of the E3’s functionality in the form of message sequence charts. Our purpose is to demonstrate how the E3’s functional entities presented in section III, interoperate during the execution of advance management procedures.

Figure 8: Example scenario for CPC information exchange between Terminal (T) and Network (N)
In Figure 8 an example scenario for the combined use of Out-band CPC and In-band CPC is shown. In the so called “start-up phase” when the terminal is switched on, it starts listening to the Out-band CPC in order to obtain basic parameters (e.g. locally available networks) for network selection and connection. After connection to a network the terminal stops listening to the Out-Band CPC and starts retrieving the In-Band CPC information within the registered network by using the on-demand procedures “CPC_Info_Request” and “CPC_Info_Answer”. Scenarios where the In-Band CPC information is broadcasted are also conceivable.

Figure 9 shows an example procedure generally applicable for self-x use cases (e.g. neighbour cell list optimisation, interference control, handover parameter optimisation, load balancing, cell outage detection and compensation) in a single RAT environment. The functional block “Self-x for RAN” is using Monitoring and Fault/Event Detection procedures to constantly check the network environment status. The Monitoring function considers all the system measurement reports. The Fault/Event Detection function detects whether a fault and/or another event (e.g. cell outage, cell interference, unbalanced network loading, inappropriate configurations, identification of a new base station, etc.) has occurred. “DSNPM” supports these procedures by providing KPIs and policies to the “Self-x for RAN”. The Decision Making function decides whether it is necessary to change the system behaviour and selects the optimisation algorithms that are to be used. The Input Data Selection calculates different input metrics and sets the start parameters for the Optimisation Algorithms. In order to enhance efficiency of the corresponding operations, knowledge of former optimisation results is also considered by the Input Data Selection function. After the execution of the Optimisation Algorithms and the resulting Parameter Configuration, the possibility of reconfiguration is checked between “Self-x for RAN” and “RCM-N” and a corresponding command is sent to “JRRM-N”. Finally, “Self-x for RAN” and “DSNPM” are informed about the new configuration. This procedure is generally applicable for all self-x (single RAT) use cases and described using the example of “Cell Outage Compensation”.

Figure 9: Example procedure for Self-x Use Cases
10 presents the principal procedure of “Cell Outage Compensation” and the relation to the corresponding “Self-x for RAN” functionalities. “JRRM-N” provides “Self-x for RAN” with information on radio parameter settings of neighbour cells (TX power, antenna tilt …) and range and granularity of these radio parameters for the initiation of the Cell Outage Compensation algorithm. Information on cell individual power offset for handover and link level offset between cells is exchanged between “Self-x for RAN” and “JRRM-N” and “RCM-N” resulting in the corresponding reconfiguration execution. Success criterion is the reassignment rate of terminals affected by the outage.

Finally, figure 11 shows the example for the reconfiguration of a FBS for inter- RAT handover (e.g. for load balancing, cell outage compensation, etc.) during operation. This scenario might take place when a Single-RAT procedure failed to reach a satisfactory result.

After start-up of the blocks of the system, context information is already exchanged between the different building blocks. In the next step, the Self-x for RAN configures load measurements via JRRM-N towards the different cells in the different RATs. Load measurements are then sent from the different RATs to JRRM-N and Self-x for RAN, e.g. periodically as well as event based (i.e. triggered when certain load thresholds are crossed).

Self-x for RAN evaluates the load measurements and, in the case of detecting an unbalanced usage of the resources, initiates an intra RAT load balancing procedure. In case which an intra RAT load balancing does not provide sufficient performance results, DSNPM is informed that there may be a need for a reconfiguration of the network or a base station ("Context Notification").

DSNPM evaluates the current network status and tries to find a better configuration. This may include the usage of a different or additional spectrum which has to be negotiated with the DSM ("Spectrum Assignment Request", "Spectrum Assignment Answer").

If DSNPM decides that the network or base station has to be reconfigured, a reconfiguration command is sent to the RCM-N. In the case that only some parameters need to be optimised or reconfigured, the RCM-N directly instructs the underlying RATs to do so.
In the case of a larger reconfiguration, e.g., a base station or part of it has to be reconfigured to another RAT (e.g. LTE instead of UMTS), the RCM-N instructs JRRM-N to offload all traffic to other cells in order to avoid service interruptions. After sending access selection decisions/handover commands to the terminals and supervising the success of the handovers, the JRRM-N reports to the RCM-N that the traffic is offloaded and then the RCM-N executes the reconfiguration in the underlying RATs ("Reconfiguration enforcement/execution").

![Diagram of single-RAT procedure and inter-RAT handover process](image)

**Figure 11:** Message Sequence example for the reconfiguration of a base station for inter-RAT handover

VI. **Assessment of Cognitive Systems**

In this section we will discuss on the assessment of cognitive systems and give a short overview on our approach to evaluate and compare systems and point out new challenges introduced by new, self-x and cognitive characteristics compared to traditional communication systems.

The described cognitive and self-x systems are communication systems and at the same time complex software systems, hence test and evaluation of such system should be based on well-known methods from both areas.

From the software design we can use the consideration of the complete life-cycle of a system, the modular approach for design and implementation as well as the provision for dependencies between functions. Design and implementation of cognitive and self-x firstly address only the substrate, which are the hardware platforms (e.g. software defined radio components) or interfaces and protocols available between the distributed parts of the system (e.g. between terminal and base station). Later system behaviour is founded here, while the actual operation is based on policies, which are implemented in a second step. A design process based on use cases and the integration of traceability VII in the software design and evaluation phase will link different part of the system together and make dependencies visible. Even in complex systems this allows detecting, if all requirements are met and identifying causes for a specific system operation.

As of today there is no complete theory behind design and operation of cognitive network element and functions. Some paradigms are already known VII, such as the operation based on context and the closed control loop. System operation is based on using a wide range of pre-defined solutions or finding new
solutions, e.g. by learning. Especially in communication systems, the algorithms, which are controlling the system, might be distributed and composed of other, possibly also cognitive functions. The result will be a system composed of interrelated, tangled loops, which needs to offer the required functionality with the desired quality of service, in a stable and foreseeable way.

From testing communication systems we can use the approach of generating test traffic and the interworking of a system under test with test environment VII. In our case of cognitive and self-x systems, this generation is about the creation of an environment, in which the system operates or the creation of clearly defined situations (e.g. a white space for opportunistic communication or the event of a cell outage in a 3G network). For practical testing of an implemented system, based on above mentioned paradigms, we need to identify three types of interfaces VII: The context interfaces, the system operation is based on, the interface to inject policies towards the system, by which the system operation is controlled and an interface towards the internal state or knowledge of the system. The latter is needed to control and reset the system behaviour in case of repeating tests of a self-adaptive system.

Adaptation methods used for data transmission over channels with fluctuating characteristics are well-known and widely used (e.g. power control in UMTS, rate control in WLAN). Beyond that, the focus of the E3 architecture is on self-management of the network devices. Basically self-managed systems use self-adaptation processes to change the system operation by changing the system itself (e.g. by learning, genetic algorithms), which influences the system’s operational characteristics and behaviour. Of course, a self-managed system is expected to deliver services with the same or even better performance compared to traditional systems. We can compare two implemented systems directly by their performance characteristics, e.g. how they can exploit available resources and the impact on operational expenses. But the possibility of a system to react on a wide range of pre-defined situation or even detect new solutions, lead to a new metric for comparing network devices: The ability of a system to solve (domain specific) problems. This metric is also related to the operational expenses, e.g. how much manual intervention for network management is still needed. Additionally, the metric is related to the confidence or trust in autonomic system operation. For the practical assessment of an implemented system we use a series of benchmarks VII that represent situations by the environment for the system. Based on the complexity of the benchmark, we derive the level of autonomicity.

To summarize, we identified three main topics for evaluation of cognitive and self-x systems:

- Assessment of the functionality during the design and implementation process: Based on use cases and other software engineering methods, one can check if all required functionalities are covered by the system and reasons for system behaviour can be traced.
- Isolation of cognitive and self-x control function within the implemented system: Interrelated, distributed functionalities as well as their internal, complex state necessitate the isolation of part of the system and the control of internal knowledge for performing and repeating all kinds of performance measurements and tests.
- Assessment of the implemented system: In addition to standard performance measurements, the self-managed system is evaluated according to its ability to solve problems. As a result an operator can trust the system operating with reduced or without human intervention.

VI.1 Application to the E3 Architecture

To illustrate the approach, it will be first shown how the assessment interfaces can be mapped, based on the E3 functional architecture. The assessment described here is used to evaluate an implementation, not the
architecture itself. The assessment is applicable to architectural blocks and implemented functions which (can) include self-x or cognitive algorithms. For an example we will have a closer look on Self-x for RAN.

The functional architecture shown in Figure 2 can be used to locate the Self-x for RAN block and its relation with surrounding functional blocks. To apply the assessment process for a specific implementation of a function block it is needed to isolate this function by identifying all interfaces to interacting function blocks. In case of the Self-x for RAN the interfaces are MX, XJ, XC. Note that it might be also possible to evaluate groups of functions of one or more system, like closely related functions (e.g. network planning together with resource management) or peer entities in different sub-systems (e.g. Self-x for RAN supporting functions in terminal together with Self-x for RAN in a base station).

Based on additional information from message sequence charts (compare with high-level example in Figure 9), we can differentiate between interfaces for controlling or coordinating between systems (such as the MX interface between DSNPM and Self-x for RAN), interfaces for acquisition of necessary information (the XJ interface) or interfaces related with the configuration of devices (the XC interface). These complex interfaces can be based on a number of real interfaces or protocols and can even handle different procedures. In summary, there will not be a one-to-one mapping of interfaces needed for the assessment and the interfaces of the E3 architecture, but these interfaces will help to understand the interaction between functional blocks and transferred data.

From the assessment point of view, the implemented function inside the Self-x for RAN is controlled by policies, which are delivered via the MX interface from the DSNPM. The basis for decision making of the algorithm is the context from the JRRM, acquired via the XJ interface. The result of algorithmic operation can be monitored on the XC interface between the Self-x for RAN and RCM. In the practical execution of the assessment process, these interfaces will be used to present operational situations (problems) to the Self-x for RAN function that need to be solved by the (implemented) cognitive system

VII. Conclusions

Future mobile networks will have an increased complexity that calls for advanced network management mechanisms. In the context of the E3 project we based out efforts to produce these mechanisms in three enabling technologies namely cognition, autonomicity and reconfigurability. As a result, we have produced an architecture that covers future requirements and improves the overall performance of the network. In this paper we presented the functional architecture and its mapping to existing standards and provided examples related to its operation. Moreover, we have discussed elements of the adopted information model, provided information about the E3’s cognition and self-x capabilities and also described issues related to the assessment of these cognitive functionalities. The major contribution and also award of the presented work lies in the fact that proposed architecture has been approved as a feasibility study by a major standardisation group such as ETSI RRS, which in addition, has recently received the mandate to proceed with its standardisation.

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References

[3] 3GPP TS 32.500, Telecommunications Management; Self Organizing Networks (SON); concepts and requirements, 0.3.1, 23-07-2008


[32] E3 Deliverable D3.2 “Algorithms and KPIs for collaborative cognitive resource management”
[37] Aaron B. Brown, Joseph Hellerstein, Matt Hogstrom, Tony Lau, Sam Lightstone, Peter Shum, Mary Peterson Yost, "Benchmarking Autonomic Capabilities: Promises and Pitfalls", First International Conference on Autonomic Computing (ICAC'04), pp.266-267, 2004


