Architecture and Enablers for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks: The IEEE 1900.4 Working Group

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ABSTRACT

Over the past decade or so, the wireless industry has undergone many significant changes. Radio systems have moved toward forming heterogeneous wireless networks: collaborations of multiple radio access networks, which in some cases operate different radio access technologies, such as second- and third-generation cellular RATs, IEEE 802.x wireless standards, and so on. On the other hand, multimode reconfigurable user devices with the ability to choose among various supported RATs have become a reality, and devices and networks with dynamic spectrum access capabilities, allowing real-time sharing of spectrum resource usage among different systems, are expected to be a part of the future radio eco-space. As a result of these changes, there is a need to develop a standard that addresses the requirements and leverages the opportunities posed by such a versatile radio environment. To this end, IEEE 1900.4 aims to standardize the overall system architecture and information exchange between the network and mobile devices, which will allow these elements to optimally choose from available radio resources. In other words, the standard facilitates the distributed dynamic optimization of the usage of spectrum offered by the heterogeneous wireless network, relying on a collaborative information exchange between networks and mobile devices, thereby acting as a common means to improve overall composite capacity and quality of service for the served networks. This article provides a snapshot of IEEE P1900.4 in its current form, covering the scope and purpose of the standard, reference use cases for which the standard is applicable, its system and functional architectures, and finally, the information model for its main interfaces.

INTRODUCTION

The 1900 projects form a new standards series within the IEEE, established in 2005 jointly by the IEEE Communications Society and IEEE Electromagnetic Compatibility Society. The objective of 1900 is to develop standards in the areas of dynamic spectrum access (DSA), cognitive radio (CR), interference management, coordination of wireless systems, and advanced spectrum management, among others. In March 2007 the 1900 series was placed under the newly formed IEEE Standards Coordinating Committee 41 (SCC 41), "Dynamic Spectrum Access Networks" [1].

Currently, there are two standards and four Working Groups (WGs) within the remit of SCC 41. Of these, IEEE 1900.1, "Standard Definitions and Concepts for Dynamic Spectrum Access: Technology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management," was completed in September 2008, and IEEE 1900.2, "Recommended Practice for the Analysis of In-Band and Adjacent-Band Interference and Coexistence Between Radio Systems," was approved by the IEEE Standards Board in March 2008. The 1900.3 WG is continuing work on "Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules," and two recently added WGs are 1900.5, "Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications," and 1900.6, "Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and Other Advanced Radio Communication Systems."

The IEEE 1900.4 WG [2] was formed in February 2007, originating from the 1900.B study group [3], and entitled "Architecture and

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Enablers for Optimized Radio and Spectrum Resource Usage." Approaches, concepts, and architectures serving as a basis for the 1900.4 WG have been extensively studied in the European projects End-to-End Reconfigurability (E^2R II) and End-to-End Efficiency (E^3) [4], and in Japanese projects on SDR and CR systems [5]. As the title implies, the 1900.4 WG has aimed at standardizing architectures and functions for distributed decision making in order to optimize radio resource usage [6–9]; the first task of 1900.4 is to develop a standard on "Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks." This is the subject of the article at hand.

Three reference use cases have been defined within IEEE 1900.4 [10]: dynamic spectrum assignment, dynamic spectrum sharing, and distributed radio resource usage optimization. Based on these use cases, the system requirements and corresponding system architecture, functional requirements and corresponding functional architecture, and the information model for interfaces between 1900.4 entities have been developed.

This article provides a snapshot of 1900.4, where it is noted that the developing (draft) standard might be subject to minor refinement before publication. The next section of this article presents the motivation, scope, and purpose of this standardization project, while the following section discusses the main system assumptions and corresponding approaches within 1900.4. We then describe the three reference use cases currently considered within the project, thereby further illustrating its scope and purpose. The following two sections present the system requirements and derived system architecture for the standard, while an overview of the functional architecture is then given. The corresponding information model for 1900.4 is then briefly described, before the final section concludes and discusses future steps.

MOTIVATION, SCOPE, AND PURPOSE

Multimode reconfigurable mobile devices are increasingly being adopted within the wireless industry. The choice among various supported air interfaces on a single wireless device is already a reality today, with many devices offering, for example, second- and third-generation cellular radio access technologies (RATs) as well as IEEE 802 wireless standards, among others. Furthermore, user devices and networks with DSA capabilities are emerging, allowing the sharing and/or optimization of spectrum usage among different systems, and such capabilities will play an increasing part in the wireless world in the near future. One good example of such a facet is the developing IEEE 802.22 standard for wireless regional area networks (WRANs), serving broadband communications for remote communities, effectively achieved through a CR idiom.

Based on the above observations, there is a need to develop a standard leveraging the opportunities, and addressing the technical and regulatory challenges brought about by this newfound versatility in the radio environment. To this end, as broadly outlined in the Project Authorization Request (PAR) of IEEE 1900.4 [2], the objective is to define the building blocks comprising network resource managers, terminal/device resource managers, as well as the information to be exchanged between these building blocks, to enable coordinated network-device distributed decision making. It is intended for this to target the optimization of radio resource usage, including spectrum access control, in heterogeneous wireless access networks. It is hoped that through such an approach, the developing standard will improve overall composite capacity and quality of service of wireless systems in a multiple radio access network (RAN) environment, where this environment might comprise more than one RAT.

It is noted that thus far, 1900.4 has been limited to architectural and functional definitions; the corresponding protocols related to the information exchange between 1900.4 elements, as well as other complementary aspects of the standard, will be addressed at a later stage in the standardization process.

SYSTEM ASSUMPTIONS AND APPROACH

IEEE 1900.4 is intended to apply to a heterogeneous wireless environment, such as that depicted in Fig. 1. Such an environment may include multiple operators, multiple RANs, multiple RATs, and multiple terminals. As the main subject of optimization, advanced spectrum management capabilities are considered in 1900.4; an example of such a capability is that the assignment of spectrum to RANs can be dynamically changed, where "spectrum assignment" may be characterized as a carrier frequency, a signal bandwidth, or a radio interface to be used in the assigned spectrum. Another example of advanced spectrum management is where assignment of spectrum to RANs is fixed, but some RANs are allowed to concurrently operate in more than one spectrum assignment. For backward compatibility, RANs in 1900.4 might be a legacy technology.

Terminals to which 1900.4 is applicable are reconfigurable, with or without multihoming capability, where multihoming is defined as the capability of a reconfigurable terminal to have more than one simultaneous active connection with RANs. Again, for backward compatibility, 1900.4 does not rule out legacy terminals coexisting in the network. This is an important consideration, ensuring smooth progression to adoption of the standard.

The underlying approach in 1900.4 is to define a management system that decides on a set of actions required to optimize radio resource usage and quality of service in a heterogeneous wireless environment. In particular, 1900.4, in its first stage, defines the entities and interfaces of this management system. The two key management entities are shown in Fig. 1: these are the network reconfiguration manager (NRM) and terminal reconfiguration manager (TRM). The

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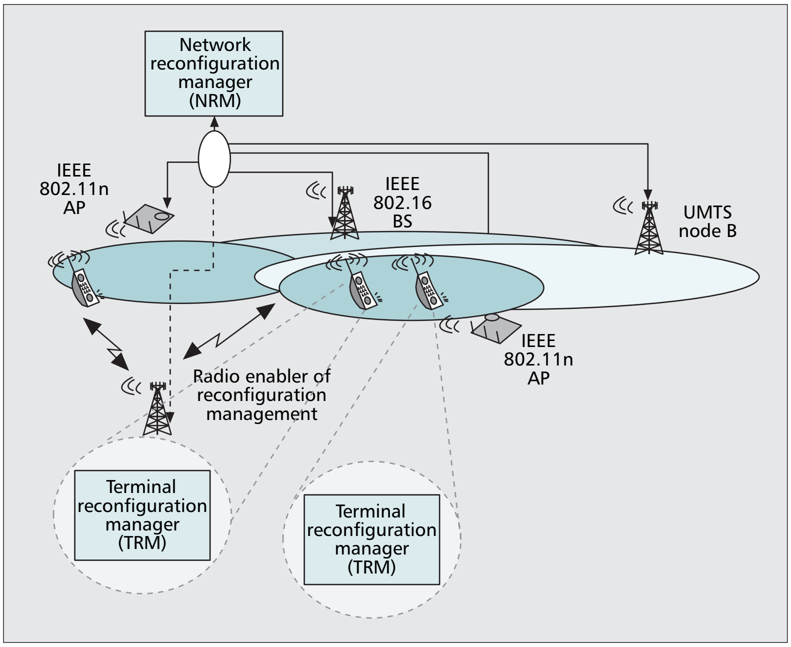


Figure 1. *The heterogeneous wireless environment considered within P1900.4.*

composition of a heterogeneous wireless environment with 1900.4 management entities creates a composite wireless network (CWN), which includes various capabilities to optimize radio resource usage as well as the associated flexibility.

The developing standard from 1900.4 uses a distributed approach to radio resource optimization, where reconfiguration decisions are made by terminals as well as the network. The key interface enabling such optimization is the interface between the NRM and TRM. The standard also defines a logical communication channel corresponding to this interface, termed the radio enabler (RE) [11]. The RE may be mapped onto:

- One or several legacy RANs already being used for data transmission
- One or several RANs or RATs dedicated to the RE

In the former case, the in-band solution, the RE can be realized through existing channels, for example, the broadcast control channels of the GERAN. In the latter case, the out-band solution, the RE might alternatively be mapped onto a newly defined dedicated physical channel. The latter case is depicted in Fig. 1 using dotted lines.

Reference Use Cases

As has been stated, IEEE 1900.4 defines three use cases: DSA, dynamic spectrum sharing, and distributed radio resource usage optimization. These use cases are depicted in Fig. 2.

We outline the considered use cases as follows.

Dynamic spectrum assignment provides the process and mechanisms to dynamically assign frequency bands to RANs within the CWN, operating at a given location and time. This is, of course, in compliance with regulatory rules. For instance, this use case may cover situations where:

- A new carrier is added for 3G access.
- A frequency band previously used for 3G is assigned to mobile broadband wireless access (e.g., IEEE 802.16e).
- The network switches the usage of a spectrum band from mobile broadband wireless access (e.g., IEEE 802.16e) to a wireless LAN (e.g., IEEE 802.11n) if a large number of wireless LAN terminals are suddenly close to the wireless LAN access point.

Dynamic spectrum sharing provides the process and mechanisms for a type of spectrum access that occurs when different RANs and terminals dynamically access spectrum bands that are overlapping, in whole or in part, causing less than an admissible level of mutual interference. This is again, of course, in accordance with regulatory rules, and may be done with or without negotiation. Examples pertinent to this use case may cover:

- Unlicensed secondary systems (e.g., IEEE 802.22) accessing licensed but locally unused VHF/UHF spectrum bands in an opportunistic fashion
- Unlicensed wireless LANs (e.g., IEEE 802.11 in a possible future CR-like variant) accessing licensed but locally unused VHF/UHF spectrum bands in an opportunistic fashion.

The *distributed radio resource usage optimization* use case covers the process and mechanisms by which the optimization of radio resource usage is performed by the CWN and terminals in a distributed manner. This is done at two levels: the network and terminals. The NRM, at the network level, derives radio resource usage constraints and evaluates them in order to meet a global objective (e.g., global network power minimization or load balancing). These radio resource usage constraints are conveyed from the NRM to the TRM via the RE. At the second level of optimization, end-user terminals optimize their use of radio resources (radio links, spectrum bands, and channels) by selecting in turn the optimal (or optimal combination) of resources, say, to yield maximal throughput or required quality of service (QoS), and/or satisfy user preferences. These choices also have to be compliant with policies derived at the first level (the NRM) and must respect a "time constraint" provided by the NRM within which the policies must be executed. An example of this use case is where the CWN context changes, and remaining users adapt to optimally use available resources (e.g., when users arrive/leave the CWN).

Based on these described use cases, the system requirements and corresponding system architecture of 1900.4 are derived; these are the subjects of the next two sections.

System Requirements

The advanced spectrum management considered in IEEE 1900.4 assumes that reconfiguration of some parts of the CWN is possible (e.g., base stations and terminals). Reconfiguration usually involves three phases: obtaining the context information required for decision making, making reconfiguration decisions, and the actual reconfiguration according to the decisions made. These three categories are used to classify the system requirements of 1900.4.

Context Awareness

The draft standard for IEEE 1900.4 states that there shall be entities on the network side and terminal side responsible for context information collection. Two types of context information are defined: RAN context information and terminal context information.

RAN context information may include:
- RAN radio resource optimization objectives
- RAN radio capabilities
- RAN measurements
- RAN transport capabilities.

Terminal context information may include:
- User preferences
- Required QoS levels
- Terminal capabilities
- Terminal measurements
- Terminal geo-location information
- Geo-location-based terminal measurements.

The context information collection entity on the network side provides RAN context information to the NRM, while the context information collection entity on the terminal side provides terminal context information to the TRM. The NRM and TRM exchange their context information.

Decision Making

According to the draft standard, there is an entity on the network side, the NRM, which is responsible for managing the CWN and terminals to achieve network-terminal distributed optimization of spectrum usage. There is also an entity on the terminal side, the TRM, responsible for managing the terminal for network-terminal distributed optimization of spectrum usage. The TRM manages the terminal within the framework defined by the NRM, and in a manner consistent with user preferences and available context information.

Distributed decision making in 1900.4 is based on a policy-based management framework. Two types of policies are defined: spectrum assignment policies and radio resource selection policies. Spectrum assignment policies adhere to regulations and express operator objectives related to dynamic spectrum assignment. These policies are generated by another entity on the network side and transmitted from this entity to the NRM. Radio resource selection policies guide terminals in their reconfiguration decisions, and are generated by the NRM and transmitted from the NRM to TRMs in terminals. Spectrum assignment policies are mandatory for the NRM, while radio resource selection policies are mandatory for the TRMs.

Reconfiguration

The developing standard for 1900.4 requires that there are entities on the network side and terminal side responsible for reconfiguration. The reconfiguration entity on network side controls the reconfiguration of RANs, based on requests from the NRM, while the reconfiguration entity on the terminal side controls reconfigurations of

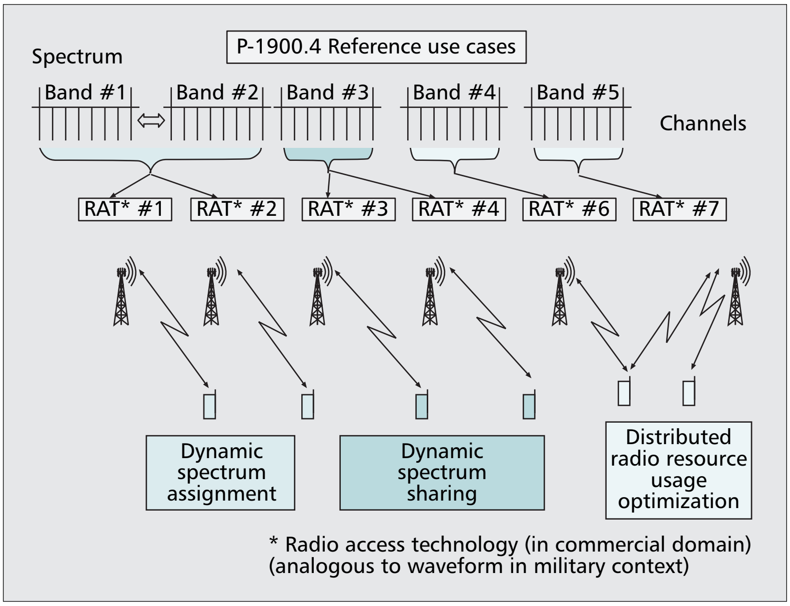


Figure 2. *The reference use cases for P1900.4.*

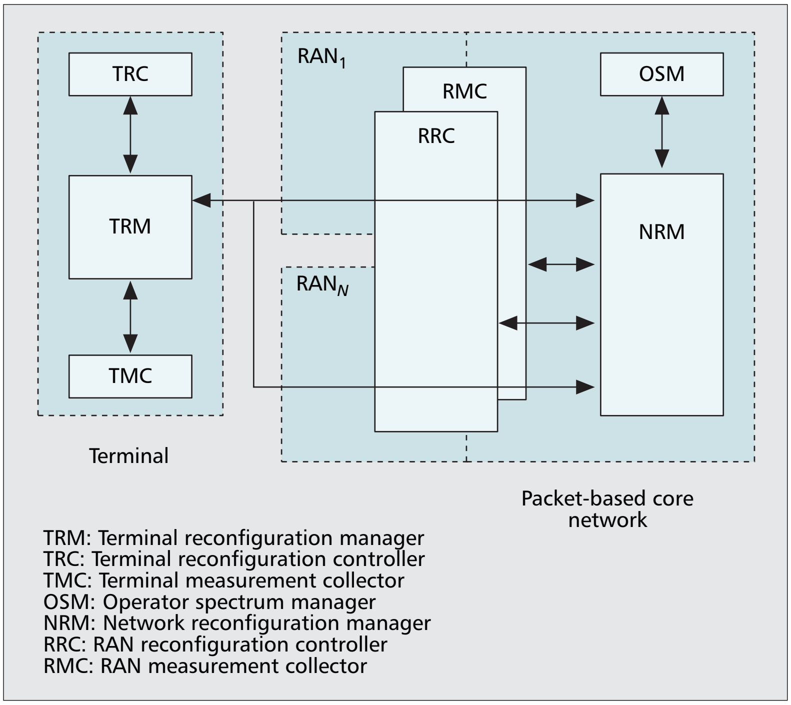
terminals based on requests from the TRM. To ensure stable network operation during reconfiguration, the maximum time interval during which reconfiguration must be performed can be specified by radio resource selection policies. Reconfiguration of the terminal must be performed within this time interval, measured from the point in time at which these radio resource selection policies are received.

System Architecture

The system architecture defined in the current draft standard for 1900.4 is depicted in Fig. 3. This specifies seven entities and six interfaces. The standard's interfaces ensure interoperability of equipment from different manufacturers covering different parts of the 1900.4 system.

Four entities are defined on the network side: the operator spectrum manager (OSM), RAN measurement collector (RMC), NRM, and RAN reconfiguration controller (RRC).The OSM enables the operator to control the NRM's dynamic spectrum assignment decisions. The RMC collects RAN context information and provides it to the NRM, and may be implemented in a distributed manner. The NRM manages the CWN, as well as terminals, regarding network-terminal distributed optimization of radio resource usage and QoS improvement, and may also be implemented in a distributed manner. The RRC icontrols reconfigurations of RANs, based on requests from the NRM, and may again be implemented in a distributed manner.

On the user device side, three entities are defined for radio resource optimization: the terminal measurement collector (TMC), TRM, and terminal reconfiguration controller (TRC), where each terminal has one TMC, one TRM, and one TRC. The TMC collects terminal context information and provides it to the TRM. The TRM manages the terminal for network-terminal distributed optimization of radio resource usage and improvement of QoS; this is done



■ **Figure 3.** *The P1900.4 system architecture.*

Interface between the NRM and TRM
From NRM to TRM • Radio resource selection policies • RAN context information • Terminal context information
From TRM to NRM • Terminal context information
Interface between the NRM and RRC
From NRM to RRC • RAN reconfiguration requests
From RRC and NRM • RAN reconfiguration responses
Interface between the NRM and RMC
From NRM to RMC • RAN context information requests
From RMC to NRM • RAN context information
Interface between the TRM and TMC
From TRM to TMC • Terminal context information requests
From TMC to TRM • Terminal context information
Interface between the TRM and TRC
From TRM to TRC • Terminal reconfiguration requests
From TRC to TRM • Terminal reconfiguration responses
Interface between the NRM and OSM
From OSM to NRM • Spectrum assignment policies
From NRM to OSM • Information on spectrum assignment decisions

■ **Table 1.** *The P1900.4 interfaces.*

within the framework defined by the NRM and in a manner consistent with user preferences and available context information. Finally, the TRC controls reconfiguration of the terminal based on requests from the TRM.

Six interfaces are defined in the draft standard (Fig. 3). These interfaces are outlined in Table 1.

Functional Architecture

The functional architecture defined in the current version of the draft standard has been derived from an array of functional requirements, which are not detailed here. This functional architecture is shown in Fig. 4. The functionalities of the OSM, RMC, RRC, TMC, and TRC are well defined in 1900.4. However, as the NRM and TRM are the key decision making entities in the standard, the 1900.4 functional description in this article concentrates on the functions of these two entities.

The main functions depicted in Fig. 4, related to both the NRM and TRM sides, are described in the following subsections.

NRM Functions

The draft standard for 1900.4 defines six functions inside the NRM: policy derivation, policy efficiency evaluation, network reconfiguration decision and control, spectrum assignment evaluation, information extraction, collection, and storage, and RAN selection.

The *policy derivation* function generates radio resource selection policies that guide TRMs in terminals' reconfiguration decisions. The radio resource selection policies are derived using the context information from the information extraction, collection, and storage function. The *policy efficiency evaluation* function evaluates the efficiency of current radio resource selection policies. Evaluation results are used by the policy derivation function in generating radio resource selection policies.

The *network reconfiguration decision and control* function makes decisions on RANs reconfiguration compliant with spectrum assignment policies received from OSM. After making these decisions, this function sends corresponding reconfiguration commands to RRC. Also, this function sends information on made decisions to OSM. The *spectrum assignment evaluation* function evaluates the efficiency of spectrum usage under the current spectrum assignment. Evaluation results are used by the network reconfiguration decision and control function in making decisions on RAN reconfiguration.

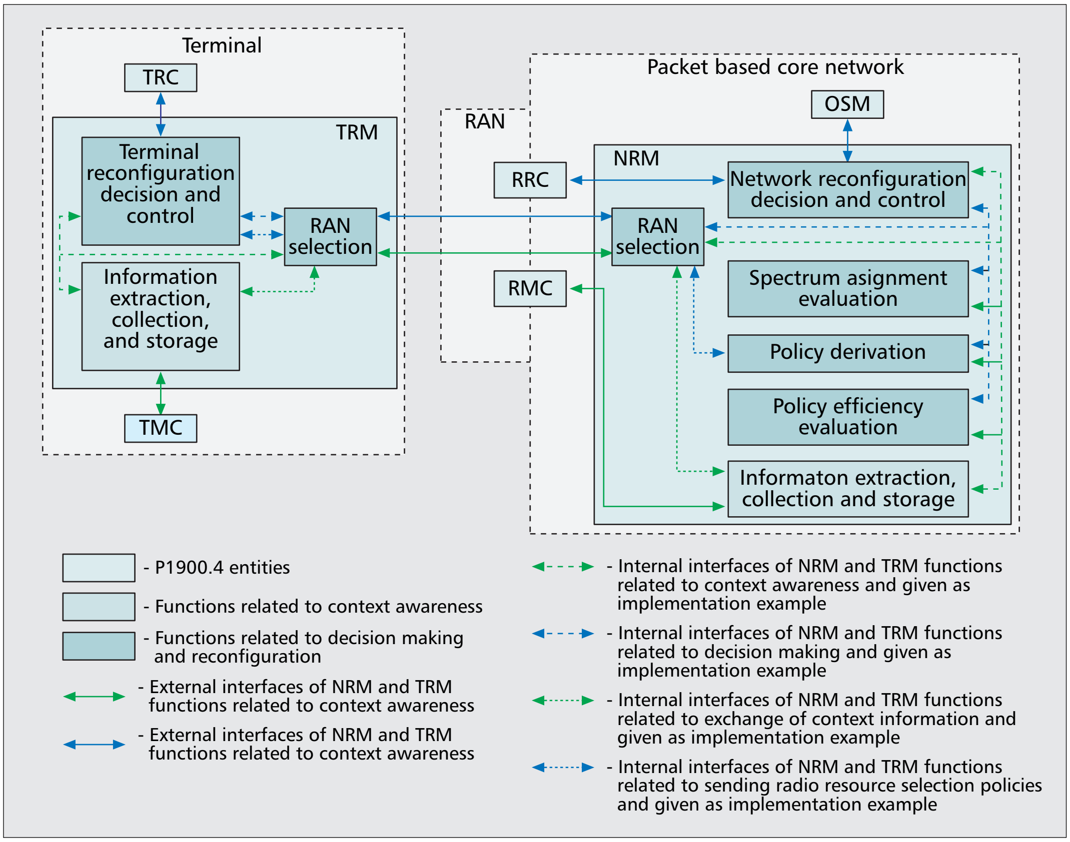


Figure 4. *The P1900.4 functional architecture.*

The developing standard for 1900.4 uses an information model based on an object-oriented approach, where terminals and the CWN are viewed as managed objects. Three key groups of classes are defined within P1900.4: policy, terminal, and CWN classes.

The NRM *information extraction, collection, and sstorage* function receives, processes, and stores RAN context information and terminal context information. RAN context information is received from the RMC, while terminal context information is received from the TRM. The NRM information extraction, collection, and storage function provides information to functions inside the NRM. It forwards RAN context information to the TRM and may forward terminal context information, related to other terminals, to the TRM.

The NRM *RAN selection* function selects RANs for exchanging radio resource selection policies and context information between the NRM and TRM. This is done to minimize signaling overhead, and ensure timely and reliable delivery of radio resource selection policies and context information.

TRM Functions

The draft standard also defines three functions inside the TRM: terminal reconfiguration decision and control, information extraction, collection, and storage, and RAN selection functions.

The *terminal reconfiguration decision and control* function makes decisions on terminal reconfiguration. These decisions are made within the framework determined by the radio resource selection policies received from the NRM. After making these decisions, this function sends corresponding reconfiguration commands to the TRC.

The TRM information extraction, collection, and storage function receives, processes, and stores terminal context information and RAN context information. Terminal context information is received from the TMC. Terminal context information regarding other terminals may be received from the NRM. RAN context information is received from the NRM. The TRM information extraction, collection, and storage function provides information to functions inside the TRM. Also, it forwards terminal context information to the NRM.

The TRM RAN selection function selects RANs for exchanging radio resource selection policies and context information between the NRM and TRM.

Information Model

The developing standard for 1900.4 uses an information model based on an object-oriented approach, where terminals and the CWN are viewed as managed objects. Three key groups of classes are defined within 1900.4: *policy*, *terminal*, and *CWN*.

Policy classes are used to abstract spectrum assignment policies and radio resource selection policies. These classes describe policies of the Event-Condition-Action type, which in this context can be envisioned as an event that triggers the evaluation of the policy condition, a condition that shall be fulfilled before applying the policy action, and the action that has to be performed if the event has occurred and the condition is fulfilled are described in these classes. *Terminal classes* abstract the user, application, device, and radio resource selection policy con-

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cepts, including, for example, such classes as user subscription, user preference, application measurements, device configuration, link, and observed channel. *CWN classes* abstract the operator and RAN concepts, including, for example, such classes as assigned channel, regulatory rule, cell, and base station.

Attributes of the 1900.4 information model classes, as well as relations between these classes, are described using class definition tables. Data types used for attributes are further defined using the ASN.1 language. The 1900.4 information model is developed in an extensible form in order to accommodate future RATs and allow custom enhancements to existing data models.

CONCLUSIONS

This article has presented a snapshot of IEEE 1900.4, outlining its purpose, scope, reference use cases, system assumptions, system architecture, information model, and other facets of the developing standard. The information presented is based on the latest version of the draft standard, which is currently in the IEEE sponsor ballot process.

The emerging IEEE 1900.4 is a baseline standard, providing the framework for detailed specification of a 1900.4 compatible system. Such a detailed specification is required to ensure interoperability of different parts of the system, as produced by different manufacturers, ensuring the objective of efficient radio resource usage optimization in a heterogeneous wireless network. Further development of this standard with specific protocols, through coming subtasks in the 1900.4 WG, is anticipated to be the main focus of future work.

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BIOGRAPHIES

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