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**Broadband Radio Access Networks (BRAN);
Study of central coordination of WAS/RLANs
operating in the 5 GHz frequency band**

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Broadband Radio Access Networks (BRAN).

Modal verbs terminology

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Introduction

Developing technologies for 5G Broadband Systems is one of the objectives of the European Commission. The EC H2020 project COHERENT [i.14], "Coordinated Control and Spectrum Management for 5G Heterogeneous Radio Access Networks" has addressed topics related to the application of the basic principles of wired Software - Defined Networks (SDN) to wireless networks.

The present document includes the main outcome of the project and the results of additional studies.

The present document does not address any regulatory issues and does not address mandatory requirements such as those related to article 3.2 of Directive 2014/53/EU [i.13].

Some results incorporated in the present document received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 671639.

1 Scope

The present document contains studies of the architectures and the protocols supporting the central coordination of WAS including RLANs (WAS/RLAN) operating in the 5 GHz bandIt also includes information provided by a radio node/network of radio nodes and the procedures for the coordination of the operation of these nodes.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] Alexandros Kostopoulos, George Agapiou, Deng Junquan, Dorin Panaitopol, Fang-Chun Kuo (Editor-in-Chief), Kostas Katsalis, Navid Nikaein, Mariana Goldhamer, Tao Chen, Rebecca Steinert, Roberto Riggio: "System Architecture and Abstractions for Mobile Networks", EU H2020 5G-PPP COHERENT Project Deliverable D2.2, July 2016.

NOTE: Available online at http://www.ict-coherent.eu/.

[i.2] Nguyen et al.: "SDN and virtualisation-based LTE mobile network architectures: A comprehensive survey", Wireless Personal Communications, vol. 86, no. 3, pp. 1401-1438, 2016.

[i.3] F. Ahmed et al.: "Distributed Graph Coloring for Self-Organization in LTE Networks", Journal of Electrical and Computer Engineering, 2010.

[i.4] P. Cardieri: "Modeling interference in wireless ad hoc networks", IEEE Communication Surveys & Tutorials, vol. 12, no. 4, p. 551-572, 2010.

[i.5] Ericsson Technical White paper: "5G systems - enabling industry and society transformation", 2015.

[i.6] 5G White Paper, white paper, NGMN Alliance, 2015.

[i.7] Antti Anttonen (Editor-in-Chief), Tao Chen, Tapio Suihko, Aarne Mämmelä, Sundar Daniel Peethala, Nidal Zarifeh, Furqan Ahmed, Junquan Deng, Ragnar Frej-Hollanti, Sergio Lembo, Olav Tirkkonen, Antonio Cipriano, Dorin Panaitopol, Per Kreguer, Akhila Rao, Rebecca Steinert, Chia-Yu Chang, Roberto Riggio, Shah Nawaz Khan, Mariana Goldhamer, Pawel Kryszkiewicz, Fang-Chun Kuo, George Agapiou, Dimitri Marandin, Yi Yu: "First report on physical and MAC layer modelling and abstraction", EU H2020 5G-PPP COHERENT Project Deliverable D3.1, June 2016.

NOTE: Available online at http://www.ict-coherent.eu/.

[i.8] IEEE 802.11™-2012: "IEEE standard for Information Technology, Local and metropolitan area networks, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.9] 3GPP TS 36.213 (V14.0.0) (2016-09): "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures (Release 14)".

[i.10] ETSI TS 136 331 (V14.3.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (3GPP TS 36.331 version 14.3.0 Release 14)".

[i.11] ETSI TS 136 214 (V14.2.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements (3GPP TS 36.214 version 14.2.0 Release 14)".

[i.12] 3GPP TS 36.423 (V14.0.0) (2016-09): "Evolved Universal Terrestrial Radio Access Network (E-UTRAN); X2 application protocol (X2AP) (Release 14)".

[i.13] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC Text with EEA relevance.

[i.14] ICT-COHERENT.

NOTE: Available at http://www.ict-coherent.eu/.

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

arc: in digraph, an ordered pair of vertices is called a directed edge or an **arc**

Central Controller and Coordinator (C3): C3 is a logically centralized entity in charge of network-wide control and coordination among entities in WAS/RLAN based on Centralized Network View (CNV)

NOTE: C3 could be implemented with physical control instances sharing network information with each other.

channel assignment: process which determines one or more frequency blocks (channels) for radio nodes

NOTE: Coexistence decision can be made when determining the channel(s) for radio nodes.

Control Plane Function: function which controls the operation of the system through appropriate messages

Control Vertex: vertex in a (di)graph which represents a C3 instance

digraph: graph which consists of a set of vertices connected by edges, where the edges have a direction associated with them

directed path: digraph, a directed path is a sequence of arcs which connect a sequence of vertices, with the restriction that all arcs in the path are directed in the same direction

dissimilar WAS/RLANs: dissimilar WAS/RLANs are WAS/RLANs that use different RATs without the same/common wireless network coexistence technologies

graph: set of vertices connected by edges

head: arc (v_i,v_j) is considered to be directed from vertex v_i to vertex v_j, v_j is called the **head** of the arc

hierarchical control: control architecture based on a central controller which coordinates the operation of other controllers

network slice instance: run-time instantiation of a Network Slice

network slice or service slice: network slice/service slice is a logical network that comprises a set of network functions and the corresponding resources required to provide **End-to-End** support for specific network services, network applications and radio configurations of WAS/RLAN

NOTE: The network services may be specific to some particular use cases or business applications. A network slice can span all domains of the network: software programs running on cloud nodes, specific configurations of the transport network, a dedicated radio access configuration, as well as settings of the WAS/RLAN devices. Different network slices contain different network applications and configuration settings.

Network View (**NV**)**:** database containing information specific to the network operation

NOTE: A Local NV includes parameters available at a local radio entity while a Central NV includes parameters available at a central controller/coordinator which are provided or resulting from the LNV.

Northbound interface (NBi): API transferring information and controls between a program running additional control application and a Controller

path: in a graph is a finite or infinite sequence of edges which connect a sequence of vertices which, by most definitions, are all distinct from one another

programmable control: function of the controller platform transferring the information from the SBi to the NBi and enabling a programmer to write control applications on top of the controller

Radio Access Network: radio access network (RAN) is part of a public land mobile telecommunication system controlled by an Operator

Radio Local Area Network (RLAN): intended to cover smaller geographic areas like homes, offices and to a certain extent buildings being adjacent to each other

NOTE: Radio LANs are also known as Wireless LANs (WLANs).

Radio Transceiver (RT): logical entity that provides radio access with full WAS/RLAN node functions

NOTE: RT can be realized by either of the combinations of R-TP, vRP and/or RTC. A set of RTs forms a radio access network (RAN/WAS) which is coordinated and controlled by C3. Some implementation examples of RTs include LTE eNBs in cellular networks or WiFi APs in the WLANs. An RT could be composed by one vRP (virtual device) and one or more R-TPs (physical devices). For example, in the Cloud-RAN (C-RAN) architecture the R-TP coincides with the RRH, while the vRP coincides with the BBU Pool. However, several other functional splits can be considered.

Radio Transmission Point (R-TP): physical entity implementing full or partial WAS/RLAN node functions while the rest of functions are offloaded to and handled by the vRP

NOTE: An R-TP may include control plane functions.

Real-Time Controller (RTC): logical entity in charge of local or region-wide control, targeting at low latency control operations such as, for example, MAC scheduling. RTC maintains the Local Network View (LNV)

NOTE: RTC can run on one RT or on a virtualized platform.

residency duration: represents the total time for a moving node to reside within the service area of a certain C3

service plane: collection of network applications and configurations of WAS/RLAN systems designed to deliver services that satisfy the needs of system users

similar WAS/RLANs: WAS/RLANs that use the same RAT or different RATs with the same/common wireless network coexistence technologies

Southbound interface (SBi): API transferring information and controls between network entities and a Controller

spectrum: within the present document the word "spectrum" indicates a combination of time-frequency resources

tail: arc (v_i,v_j) is considered to be directed from vertex v_i to vertex v_j, v_i is called the **tail** of the arc

Transport Node (TN): logical entity that is located between RTs and the core network (CN)

NOTE: A set of TNs forms a backhaul/fronthaul network whose data plane can be configured by C3. A network switch is one of the implementation examples of TN.

Virtual Radio Processing (vRP): logical entity comprising a computing platform allowing for centralized processing of full or partial RAN node functions (including the user plane and the control plane) offloaded from one R-TP or multiple R-TPs

NOTE: A vRP includes control plane functions.

weight: one value or a set of values, assigned as a label to a vertex or edge (arc) of a graph (digraph)

weighted graph: graph whose vertices or edges have been assigned weights; more specifically, a vertex-weighted graph has weights on its vertices and an edge-weighted graph has weights on its edges

weighted digraph: digraph whose vertices or arcs have been assigned with weights

Wireless Access System (WAS): defined as end-user radio connections to public or private networks. In the present document WAS and RAN are interchangeably used

NOTE: Both RAN and WAS can include RLANs

3.2 Symbols

For the purposes of the present document, the following symbols apply:

(*)	ordered sequence
{*}	unordered sequence
$\in$	is a member of
$\cup$	union
$\cap$	intersection
\	the difference of two sets
α	pathloss exponent
$a=(v_i,v_j)$	the arc a that connects an ordered pair of vertices v_i and v_j
A(G)	the arc set of a digraph G
CH_i	the i-th channel
CI_i	the i-th C3 instance
d_{ij}	the distance between the i-th and the j-th node
$D(p_1, p_2)$	the distance between two points p_1 and p_2
$e=v_iv_j$	an edge e that connects vertices v_i and v_j
E(G)	the edge set of a graph G
$\mathcal{F}$	failed spectrum usage event
G=(V,E)	a graph G that consists of a pair of vertex set V and edge set E
$I_{(tail, head)}$	interference level from tail vertex to head vertex
$I_{(vi,vj)}$	interference from vertex v_i to vertex v_j
L_i	a selection priority level of C3 instance CI_i determined by the amount of estimated available spectrum for the moving node from CI_i
L_{iPk}	distance from the i-th node to the reference point P_k
$N_{\mathcal{F}}$	number of failed spectrum usage event
$N_{\mathcal{S}}$	number of successful spectrum usage event
$N_{\mathcal{U}}$	number of spectrum usage event
$P(v_s,v_e)=(v_s,v_i,v_j,v_e)$	a path from start vertex v_s to end vertex v_e, which consists of a sequence of vertices v_s,v_i,v_j,v_e and the edges between adjacent vertices along the sequence
P_k	index of the reference point
P_{max}	transmit power of each node
$\mathcal{S}$	successful spectrum usage event
$SINR_{th}$	signal to interference plus noise ratio threshold
T_i^a	an estimated arrival time for a certain moving node to enter the serving area of C3 instance CI
T_i^r	an estimated residency duration for a certain moving node within serving area of C3 instance CI_i
T_i^{th}	a threshold of time duration for successful spectrum usage on channel CH_i

$T_{WinStart}$	a start time of estimation window
$T_{WinStop}$	a stop time of estimation window
$\mathcal{U}$	spectrum usage event
v	the vertex v
V(G)	the vertex set of a graph G
W_{ij}	weight of the arch between the i-th and the j-th node

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

3GPP	Third Generation Partnership Project
5G	5^{th} Generation Mobile Networks
AC	Access Category
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
AP	Access Point
API	Application Programming Interface
APSD	Automatic Power Save Delivery
AWGN	Additive White Gaussian Noise
BBU	Baseband Unit
BS	Base Station
BSS	Basic Service Set

NOTE: As used in [i.8].

C3	Central Controller and Coordinator
CDF	Cumulative Distribution Function
CM	Coordination Manager
CN	Core Network
CNV	Centralized Network View
COE	Coordination Enabler
CQI	Channel Quality Indicator
C-RAN	Cloud Radio Access Network
CSI	Channel State Information
CW	Contention Window
DL	Downlink
DSCP	Differentiated Services Coding Point
eNB	Evolved Node B
eNodeB	Evolved Node B
EU	European Union
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
GPS	Global Positioning System
HO	Hand-Over
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
LAA	Licensed-Assisted Access
LAN	Local Area Network
LBT	Listen Before Talk
LNV	Local Network View
LTE	Long-Term Evolution
MAC	Media Access Control
MCS	Modulation and Coding Schemes
MIB	Management Information Base
MLME	MAC subLayer Management Entity
NaaS	Network as a Service
NBi	Northbound Interface
NGMN	Next Generation Mobile Networks Alliance
NR	New Radio (3GPP name for 5G technology)

OAM	Operations and Management
PDU	Protocol Data Unit
PHY	Physical Layer
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RLAN	Radio Local Area Network
RRH	Remote Radio Head
RS	Reference Signal
RSSI	Received Signal Strength Indicator
RT	Radio Transceiver
RTC	Real-Time Controller
R-TP	Radio Transmission Point
SAP	Service Access Point
SBi	Southbound Interface
SDN	Software Defined Network
SINR	Signal to Interference and Noise Ratio
SME	Station Management Entity
SNIR	Signal to Noise plus Interference Ratio
SNMP	Simple Network Management Protocol
SNV	Slice-Specific Network View
SSID	Service Set IDentifier
STA	Station
TN	Transport Node
TP	Transmission Point
TS	Technical Standard
UE	User Equipment
UL	Uplink
UP	User Plane
vRP	Virtual Radio Processing
WAS	Wireless Access System
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WNM	Wireless Network Management
WT	WLAN Termination

4 Use cases of central control/coordination of WAS/RLAN in 5 GHz bands

4.1 Use case 1: Coexistence management between coordinated and uncoordinated WAS/RLANs

Coordinated and un-coordinated WAS/RLANs are shown in Figure 4.1, where Operator A manages its network operation (i.e. coordinated WAS/RLAN) on 5 GHz band (e.g. LAA-LTE) while private WLAN access point operates nearby (i.e. uncoordinated WAS/RLAN).

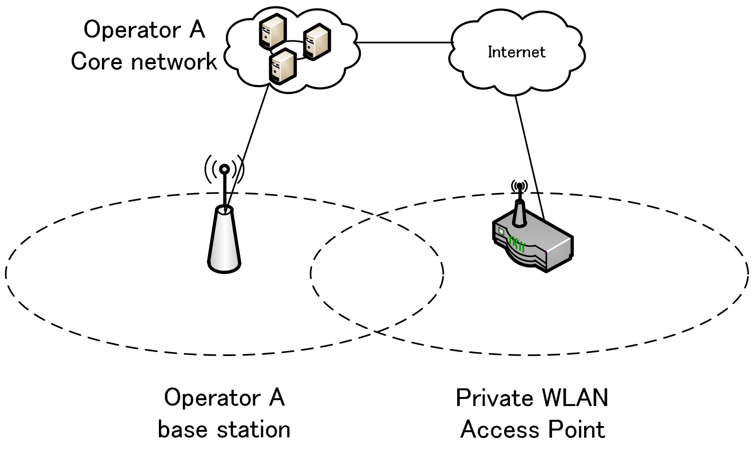

Figure 4.1: Coordinated and uncoordinated WAS/RLANs

4.2 Use case 2: Coexistence management between coordinated and uncoordinated WAS/RLANs managed by a single network operator

Similar/dissimilar WAS/RLANs managed by a single network operator are shown in Figure 4.2, where operator A network operates two LTE base stations and a 5G base station. Operator A network can also operate Wireless LAN access point by utilizing ANDSF.

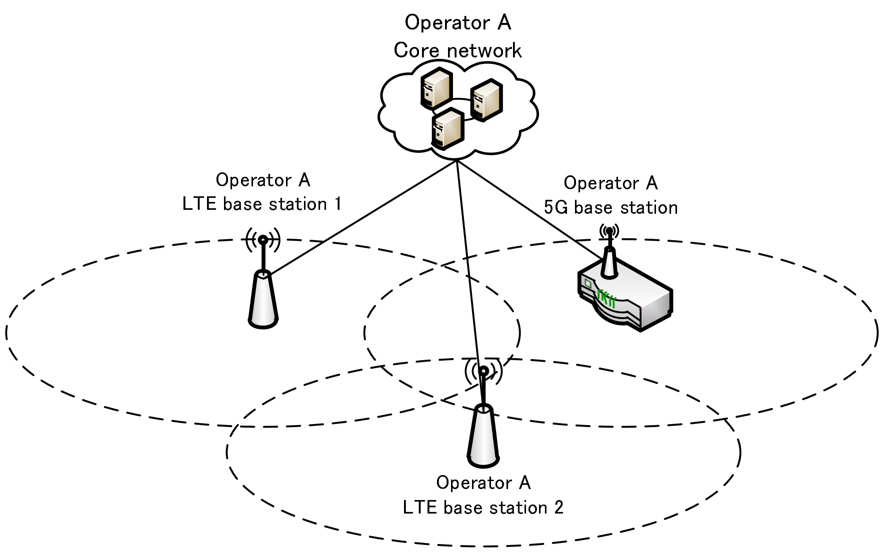

Figure 4.2: Similar/dissimilar WAS/RLANs managed by single network operator

4.3 Use case 3: Coexistence management between similar/dissimilar WAS/RLANs managed by multiple network operators

Similar/dissimilar WAS/RLANs managed by multiple network operators are shown in Figure 4.3, where operator A network operates two LTE base stations and a 5G base station while operator B operate a 5G base station, LTE base station and WLAN access point. The coexistence management between different network operators could enhance their network performance.

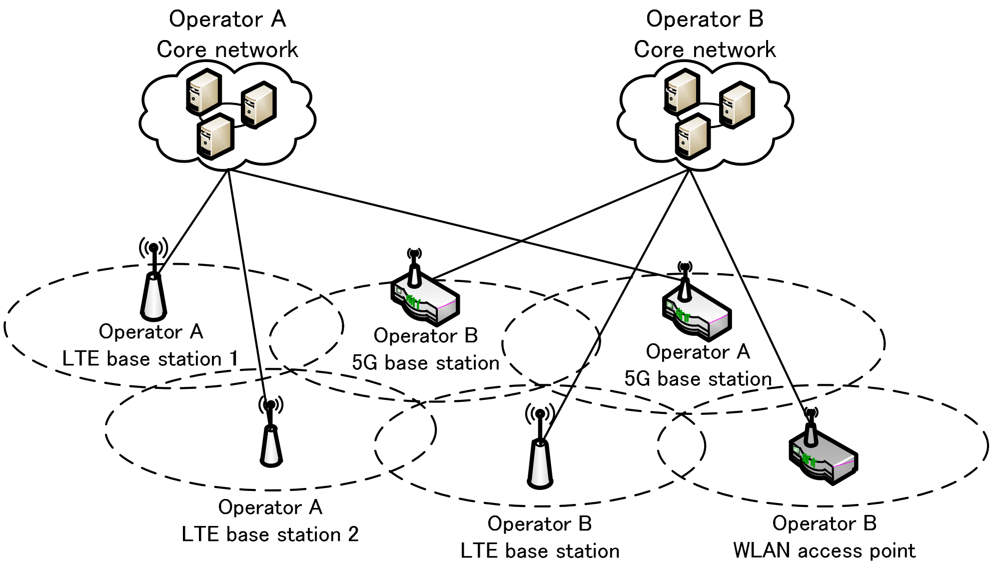

Figure 4.3: Similar/dissimilar WAS/RLANs managed by multiple network operators

5 Possible requirements

5.1 Requirements for application to WAS/RLAN in 5 GHz bands

According to the use cases as shown in clause 4, the following general requirements should be satisfied in the central control/coordination of WAS/RLAN in 5 GHz bands:

- Central control/coordination mechanism should support coexistence management between coordinated and uncoordinated WAS/RLANs.
- Central control/coordination mechanism should support coexistence management between similar/dissimilar WAS/RLANs.
- Central control/coordination mechanism should support coexistence coordination between different network operators operating WAS/RLANs in 5 GHz bands.

5.2 Other possible requirements

In order to achieve global optimization of the network operations of WAS/RLAN, the following requirements should be satisfied:

- Central control/coordination mechanism should support network management for high efficient resource utilization, which considers both radio spectrum and, when appropriate, core network resource per service slice.
- Central control/coordination should support the mechanism for low complexity spectrum reassignment, which considers spectrum transition capability within availability time period of the allocated spectrum.
- Central control/coordination should support moving radio nodes.
- Central control/coordination should support the service continuity of moving nodes, which includes serving C3 selection for moving nodes considering available spectrum and residency duration within the C3 along predicted trajectory of the moving node.
- Central control/coordination should support the quick identification of the spectrum in which a radio node can operate with high efficiency while considering the spectrum utilization pattern.

- Central control/coordination should support the spectrum assignment to increase the number of nodes whose QoS are satisfied, which considers each node's QoS requirements and the possible QoS degradation due to interference among nodes.
- Central control/coordination should support the spectrum assignment to reduce interference aggregation effect from different nodes, while considering the effect of interference aggregation.

6 Study on central control/coordination concepts

6.1 Introduction

The transposition of SDN principles to the wireless domain is not straightforward, given the specificities of the wireless network operation. In the present document are included the main outcomes of the project COHERENT related to a control framework, based on SDN principles, applicable to the operation of heterogeneous wireless technologies in the same band.

More specifically, this clause provides an overview of central control/coordination concepts applied to WAS/RLAN in 5 GHz bands.

First, the present document reviews the architecture, one of the main outcomes of the project COHERENT and implements the following concepts:

- Control plane-user plane separation;
- Abstracted view of the network;
- Service slices;
- APIs offering a common framework for developing control applications.

6.2 Hierarchical Control Concepts

6.2.1 Hierarchical Control concepts in COHERENT

The architecture introduced in [i.1] adopts a centralized solution, SDN-based, which could achieve global optimization of the wireless WAS/RLAN networks. Furthermore, by applying SDN principles to wireless networks is enabled the control programmability, i.e. a software developer is provided with the software APIs for writing control applications faster.

However, global optimization of SDN-based wireless networks comes at the expense of scalability and latency.

To address these issues, an SDN-based centralized solution has been introduced in [i.1], which employs two hierarchical control mechanisms, namely network-wide control and real-time control as shown in Figure 6.1 and could achieve global optimization of the wireless networks with higher scalability and lower latency.

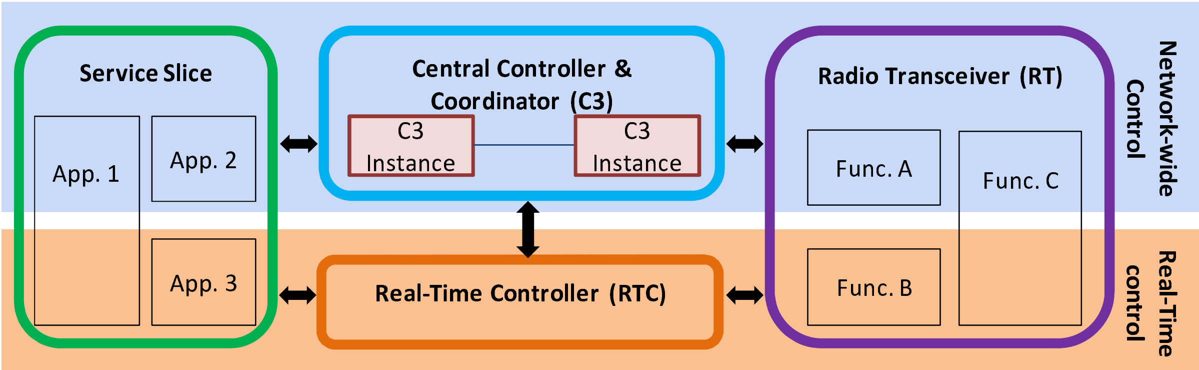

Figure 6.1: Network wide control and real-time control in hierarchical control scheme

The Central Controller and Coordinator (C3) is a logically centralized entity, which provides network-wide control/coordination for the wireless networks deployed in a given geographic area. For overcoming the scalability issues in a large and dense wireless network deployment, or for performance/reliability reasons, the logically centralized C3 can be implemented with distributed control instances sharing network information with each other. Sharing network information among C3 instances creates the logically Centralized Network View (CNV).The Real Time Controller (RTC) is a logical entity that is designed to offer real-time control to overcome the latency challenges. RTC should be close to the physical radio elements so that it could adjust to rapidly varying wireless networks. RTCs in the wireless network may not coordinate with each other and therefore network information is not shared between RTCs. In actual implementations RTC could be a separated entity or could be included into RT.

By separating control functionalities between C3 and RTC, C3 makes decisions that are related to higher latency network functionalities, while RTC handles control decisions for latency-sensitive network functionalities in radio transceivers (RTs). Moreover, different network slices contain different network service applications and configuration settings. Some application modules in network slices may be latency-sensitive. For such a slice, these modules are located in the RTC.

6.2.2 Possible enhancements to Hierarchical Control concepts

6.2.2.1 General principles

In order to meet the requirements as shown in clause 5.1, Hierarchical Control scheme in one network should consider the network coordination with another coordinated network. This is because in the 5 GHz bands the WAS/RLAN can operate on license-exempt basis, i.e. no individual spectrum planning/coordination. In order to achieve network coordination between different coordinated networks, information sharing between different coordination systems would be needed. Figure 6.2 shows the interference due to no information sharing with another Hierarchical Control system. Hierarchical Control system B is not aware of the radio node under the system A, then the radio node under the system B makes interference to the radio node under the system A.

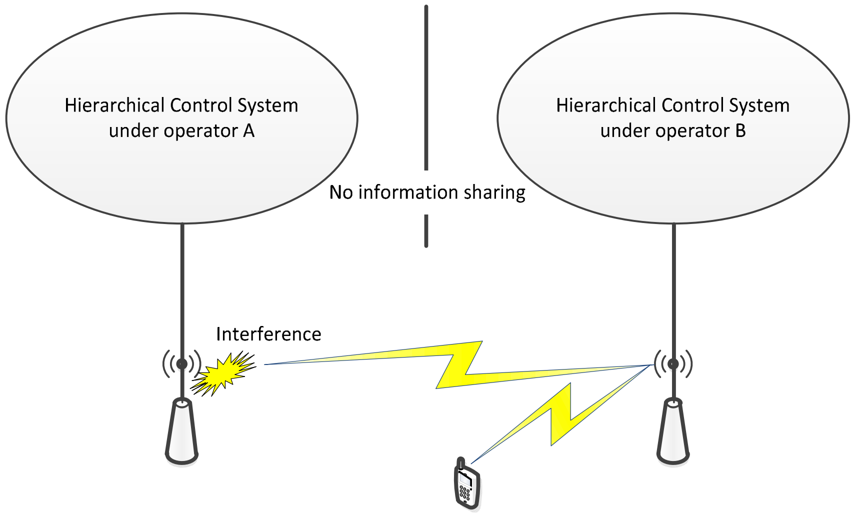

Figure 6.2: Interference due to no information sharing with another Hierarchical Control system

On the other hand, Figure 6.3 shows the case where information is shared between different Hierarchical Control Systems. The Hierarchical Control System can be aware of the existence of the radio node under another Hierarchical Control System by information sharing, then Hierarchical Control Systems can assign spectrum to their radio nodes so as not to make interference to others, each other.

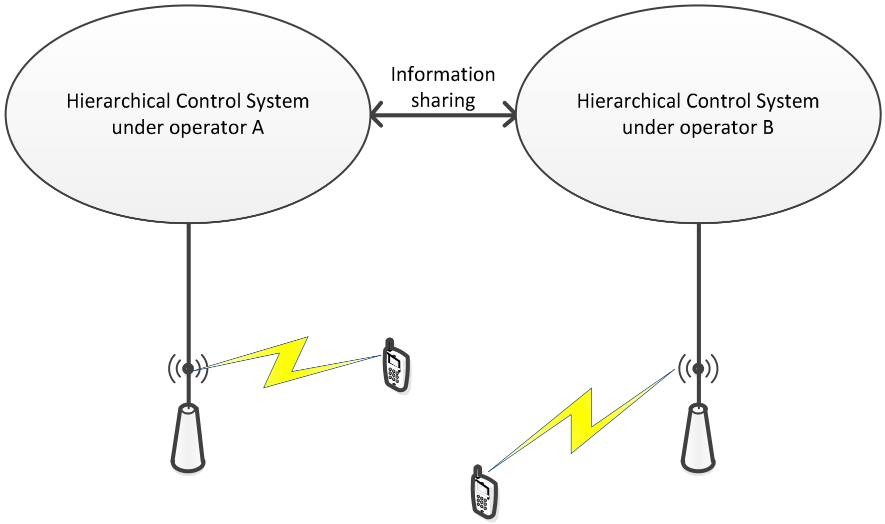

Figure 6.3: Information sharing with another Hierarchical Control system

6.3 Abstractions

6.3.1 Abstraction concepts in COHERENT

6.3.1.1 Introduction

Coordination and programmability are central concepts in SDN that are aimed to improve service quality, resource usage, and management efficiency. A good representation of the network state and infrastructure resources is crucial for effective RAN coordination and control of programmable infrastructures and services.

Abstractions encompass, for example, representations and models of time-frequency resources, spatial capabilities (i.e. number of transmit and receive antennas), as well as throughput per network slice or per allocated resources. The abstractions may also use technology-independent parameters such to enable an unified control/coordination framework.

In principle any data structure can be used for storing and accessing abstracted representation of the network state (e.g. CQI defined in LTE).

Structuring network information into network graphs in a systematic way offers effective representation of physical and virtual infrastructures. These can be applied to WAS/RLAN coordination and wide range infrastructure coordination and control operations. Essentially, network graphs enable the possibility to apply mathematical models and algorithms, which often lead to highly efficient solutions in terms of convergence and network performance [i.2] and [i.3]. Graph-based abstractions have been shown, for example, to model LTE resource allocation problems that are solved efficiently using constraint satisfaction and local search algorithms [i.3].

6.3.1.2 Conceptual overview

The concept of network graph abstractions maps horizontally and vertically at different levels of the hierarchical control architecture [i.1], [i.7]. The elements of network graphs (i.e. the vertices and edges) are created from distributed data sources such as raw metrics or the result of more sophisticated monitoring and processing functions hosted by the WAS/RLAN wireless infrastructure. A network graph is created by collecting information accessible directly from infrastructure entities and stored in some dedicated storage (e.g. storage networks and databases). At the level of RTC entities, a network graph may represent the network state relative to a certain WAS/RLAN infrastructure and associated nodes (e.g. LTE base stations or WiFi access points). Network graphs at the centralized coordination level represent the state of a defined part of the network, such as a smaller region or domain.

In the hierarchical architecture, controller instances (C3 and RTC) implement capabilities for creating network graphs for performing control operations and for providing regional or logically centralized views of the infrastructure. The capabilities include functionality for:

1) gathering network information from distributed data sources for the purpose of creating a network graph;
2) aggregating existing network graphs;
3) processing of network graphs for the purpose of coordination and control operations;
4) disseminating network graphs and results to other controllers and network entities upon request or as part of a coordination and control operation, synchronously or asynchronously.

6.3.1.3 Examples of abstractions and network graphs

6.3.1.3.1 Introduction

In the present document a graph comprises nodes and edges, where a node represents a single or a set of network elements, whereas an edge between a set of nodes may be used to represent aspects such as connectivity state, resource constraints, and interference coupling, depending on the nature of measurements, reporting and abstractions graph. An example of a network graph in a LTE deployment is provided in Figure 6.4.

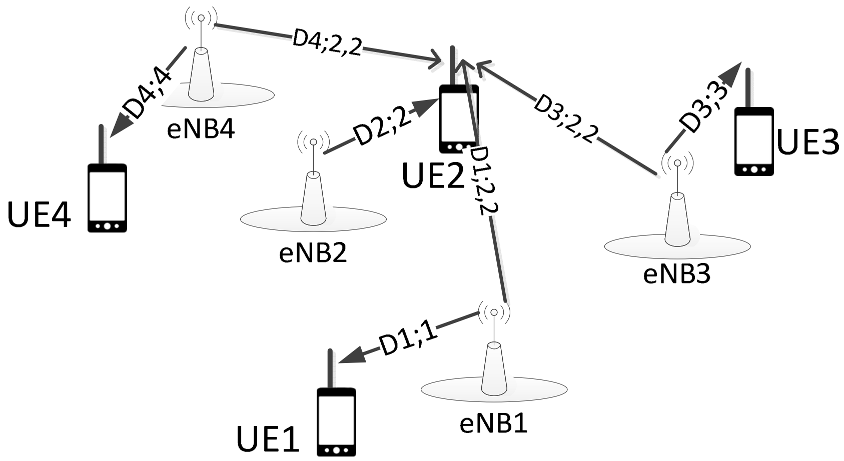

Figure 6.4: A downlink network graph

The network graph in Figure 6.4 shows the base stations (nodes or vertices) creating interference for example to UE2. The serving and interfering links are named "edges" of the network graph. The edges are noted with D (for downlink) followed by the index of the transmitting node, the index of the receiving UE and the index of the node serving the UE. In case of the edge link connecting an UE to a serving eNB, D is followed by the index of the node serving the UE and the index of the UE (receiver).

6.3.1.3.2 Nodes

As the radio network consist of different types of network elements, a node can be defined as a particular type of network element such as a base station, or a combination of network elements such as a base station and associated UEs comprising a small cell, or a D2D pair, etc. This broad definition will help us incorporate constraints related to intra-cell, inter-cell, and resource allocation. Following is a partial classification of the nodes, based on the list of network elements that are supported by the radio network.

The nodes can be divided into different categories. For LTE, the most prominent such categories are:

- UE, Remote UE, UE-to-Network Relay.
- eNodeB: Macro, Micro, Pico, Femto or Home-eNodeB.
- Relays.
- Machines.

Moreover, their characteristics can vary with respect to the following parameters:

- Radio access technology (RAT).
- Transmit powers.
- Bandwidth (carriers and resources).
- Spectrum mask.
- Subscriber group or operator.
- Noise Figure.
- Type of receiver.

6.3.1.3.3 Edges

The edges between the nodes depend on the model of the physical environment, details of measurements and the level of abstraction. In principle, it can be assumed that edges exist between all the nodes in the network. The edges at PHY-layer may represent the propagation and interference conditions that exist among the nodes, whereas the edges in MAC-layer may reflect the resource constraints between the nodes.

Edges can be qualified at different layers (PHY, MAC, etc.). There may also be dependence on the technology. Moreover, it is also possible to further label each edge with the time, frequency and spatial resource to which it is associated, as well as a time deadline for indicating when the information will be outdated.

6.3.1.3.4 Abstracted network graph

The size of the graph may be substantially reduced, by dropping edges where the interference measures are below some predefined threshold. For example, if the resource considered is spectrum, then a threshold of acceptable background signal is defined. The edge between two nodes is considered, only if the interference caused when they use the same spectrum exceeds the defined threshold. An example is given in Figure 6.5, where the nodes are WAS/WLAN entities in a homogeneous radio system, and there is an edge between pairs of WAS/WLAN entities if the annealed signal strength exceeds the threshold. Observe that, while the graph has a strong geometric structure (nearby radios tend to cause more interference than distant ones), it is not planar, nor is it defined in geometric terms. The key idea behind this abstraction is that a valid spectrum assignment is a proper colouring of the abstract graph, and an example of such a colouring is given in Figure 6.5. In other words, two cells are allowed to use the same spectral resource if and only if they are not connected by an edge in the graph.

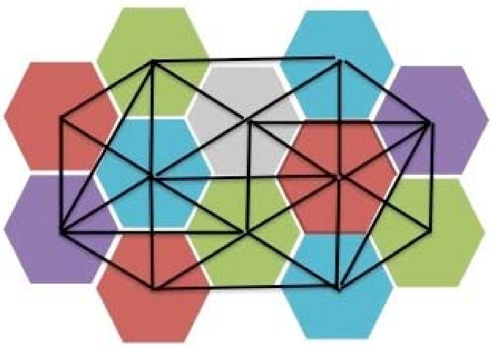

Figure 6.5: Abstracted network graph in a homogeneous network, with coloured resource assignments

Once the graph is defined, network elements such as UEs can be assigned to nodes, according to measures and estimates of network parameters that are compared to predefined threshold values. The colouring stage represents an abstraction of frequency channel assignments.

6.3.1.3.5 Overview of abstraction procedure

The nodes and edges of the network graph are the two basic components of the network graph. To build up the nodes and the edges of the graphs, the network information is abstracted, managed and maintained by the controller (e.g. C3 or RTC) through the interface between the controller and WAS/WLAN entities. For instance, when a new user joins the underlying wireless network, the configuration of this user (user identity, user capability, etc.) and the associated status (attached cell identity / AP SSID, etc.) of this user are gathered and can be used to build up a node in the network graph. When such a user sends the measurement reports that contain dynamic information on the link performance, such as measured signal power and interference power, this information is used to build up the edge between this node and other nodes. All these correlated users' configurations and statuses are maintained in order to build up the network graphs. In contrast, when a network node abruptly leaves the network, the associated configuration and status are removed accordingly and also the associated nodes and edges in the network graphs. These network graphs are used to provide abstracted information to some higher-layer applications for different purposes, e.g. mobility management, relay selection, etc. Figure 6.6 depicts how the network can be abstracted in order to build up the network graph inside the C3 instance and shows the interactions between the network management and the application. The nodes and the edges of the network graph are built based on the abstracted network information status or configuration on top of multiple underlying WAS/WLANs.

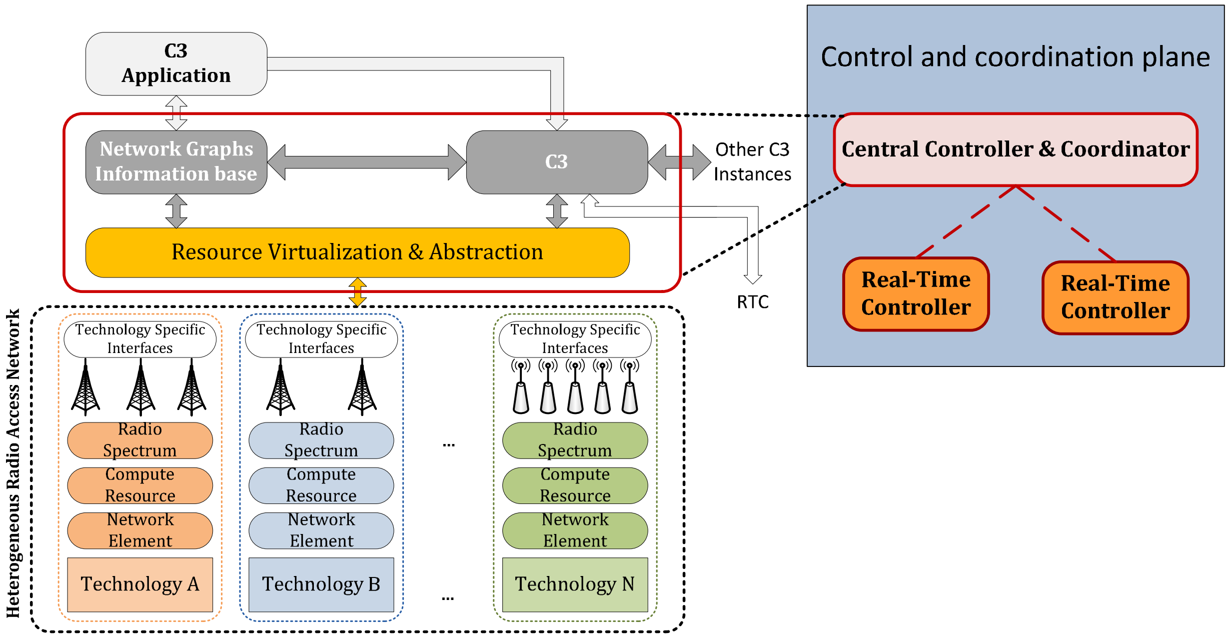

Figure 6.6: Abstraction flow for the network graph in C3 instance

6.3.2 Possible enhancements to Abstraction concepts

6.3.2.1 Examples of weighted digraph

6.3.2.1.1 Introduction

For many applications, especially for problems concerning transition of resource/state, node mobility, and interference under non-symmetric channel, it is useful to give a direction to the edges of a graph. In that case, a directed graph or, for short, a digraph is defined. A digraph is a graph consists of a set of vertices connected by edges, where the edges have a direction associated with them. Three examples of digraphs G_1, G_2, G_3 and an example of undirected graph G4 are depicted in Figure 6.7. All the examples of graphs are discussed in more detail in clause 11.

6.3.2.1.2 Directed edge or arc

In digraph, the term **arc** is used instead of edge to distinguish between the directed and the undirected case. An arc associated with tail v_i and head v_j is denoted by (v_i,v_j), see digraph G_1 Figure 6.7.

In principle, arcs are utilized to represent direction associated characters between the connected vertices.

Figure 6.7 shows the following examples of digraphs, as follows:

- G_1 shows an example of digraph, where each vertex represents a node; any two nodes v_i and v_j are associated by a directed arc if and only if the protection to higher priority nodes can still be guaranteed when the tail v_i vacates its operating channel CH_{vi} to be used by the head v_j; the tail v_i in turn uses the operating channel reassigned to it to guarantee its service continuity.
- G_2 gives another example of digraph, where each control vertex represents a candidate serving C3 instance for investigated moving node of WAS/RLAN; an arc (vi,vj), indicates that serving area of the two C3 instances are overlapped on the route L of the moving node and the moving node is supposed to move from the serving area of vi to that of vj. Consequently, G_2 shows that the service continuity for the investigated moving node can be guaranteed when the node moves from the serving area of tail v_i to that of head v_j associated by an arc (v_i,v_j).
- G_3 shows the case of interference among nodes under non-symmetric channel.

6.3.2.1.3 Weight

In clause 6.3.1.3.2, it is introduced that each edge can be labeled with the time, frequency and spatial resource to which it is associated, etc. Formally, what is labeled is called weight. With weights associated on its edges (or arcs), a graph is called an edge (or arc)-weighted (di)graph. The weight is called edge/arc weight, correspondingly.

An example of weight for edge in undirected graph can be seen in graph G_4 of Figure 6.7. Digraph G_1 shows an example of weight for arc. The weight in graph G_4 represents the ratio between real SINR and the desired SINR satisfying QoS requirement of the connected vertices.

In digraph G_1, each arc (v_i,v_j) is marked with a channel, represented as CH_{vi}, which indicates the operating channel for the tail v_i and could be vacated to be used by the head v_j.

Not only the edge/arc but also the vertex can be labeled with weight. With weights associated on its vertices, a graph is called a vertex-weighted graph. The corresponding weight is called vertex weight. In addition, there is no limit to the number of weights.

For example, in digraph G_2 of Figure 6.7, each vertex is labelled with two weights, where the first weight T^r_i represents an estimated residency duration for the moving node within serving area of C3 instance v_i and the second weight L_i represents a selection priority level of the v_i determined by the amount of estimated available spectrum for the moving node from v_i.

In digraph G_3 of Figure 6.7, both vertex and arc are associated with weights, where each vertex is labelled with a group of operating channels whereas each arc is labelled with prospective interference from tail to head.

6.3.2.1.4 Path and directed path

As an important concept in graph, a path has applications in many radio network problems, including network connectivity, transition of resource/state, and data flow control in multi-hop network, etc. The extension to path related concepts will help to facilitate more advanced RAN coordination and control to be covered.

A path in a graph is a finite or infinite sequence of edges which connect a sequence of vertices which, by most definitions, are all distinct from one another. In a digraph, a directed path is again a sequence of arcs which connect a sequence of vertices, but with the added restriction that the edges all be directed in the same direction. The length of the (directed) path represents the number of edges (or arcs) along the (directed) path. The first and last vertices of a path are called start vertex and end vertex, respectively.

For example, in digraph G_1 of Figure 6.7, there exists a directed path from v_s to v_e with length of 3 as: $P(v_s,v_e)=(v_s,v_i,v_j,v_s)$. The path with associated vertices and arc weights represents a channel transition solution. In digraph G_2 of Figure 6.7, the shortest directed path from v_1 to v_6 with length of 2 as $P(v_1,v_6)=(v_1,v_3,v_6)$ gives a sorted group of serving C3 for the investigated moving node.

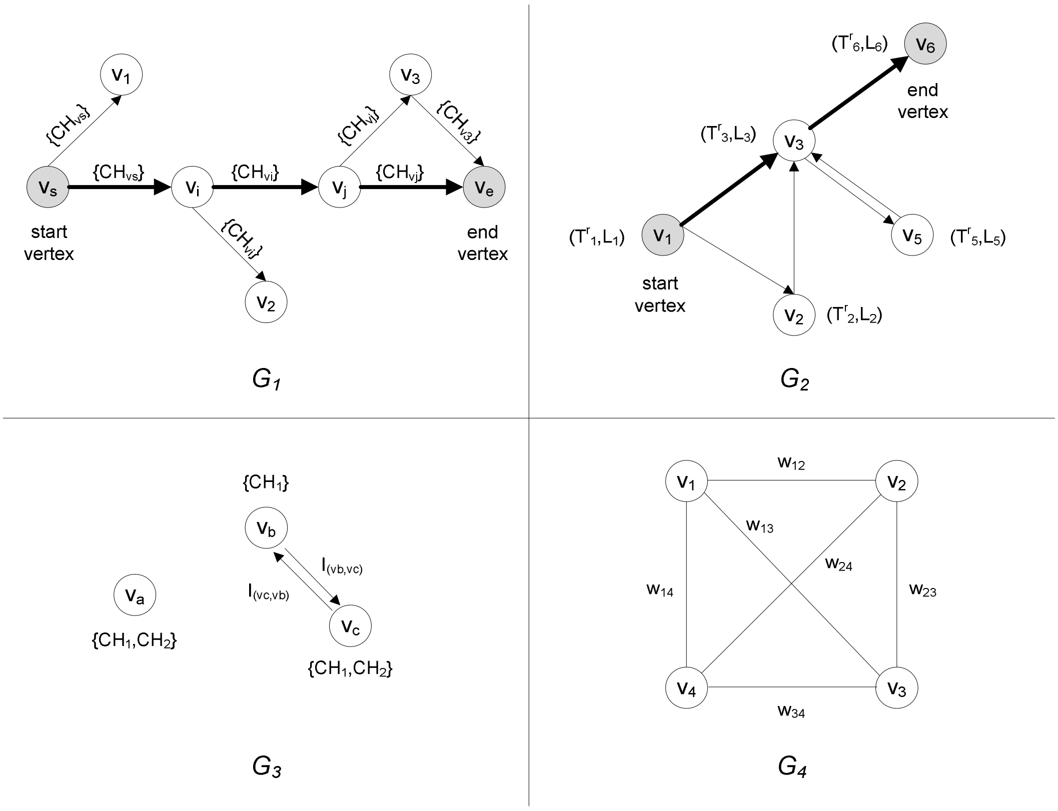

Figure 6.7: Four examples of graphs

6.4 Network Slicing and Slice-Specific Network View

6.4.1 Network Slicing and Slice-Specific Network View in COHERENT

The industry consensus is that by 2020 there will be the emergence of a new 5G radio access standard, where the 5G network of the future will involve the integration of several cross-domain networks and the 5G systems will be built to enable logical network slices for delivering specific services across multiple technologies. This will enable the mobile network operators to provide networks on an "network as-a-service" (NaaS) basis and meet the wide range of use cases that the 2020 timeframe will demand [i.5], [i.4] and [i.6].

The Network Slices envisioned within the present document span the whole protocol stack from the underlying (virtualized) hardware resources up to network services and applications running on top of them. This approach is aligned with the industry and telecom perspective, towards 5G [i.4], in order to meet the demands of the extremely diverse Use Cases. A Network Slice is a composition of adequately configured network functions, network applications, and the underlying cloud infrastructure (e.g. physical, virtual or even emulated resources, RAN resources, etc.), that are bundled together to meet the requirements of a specific use case or business model.

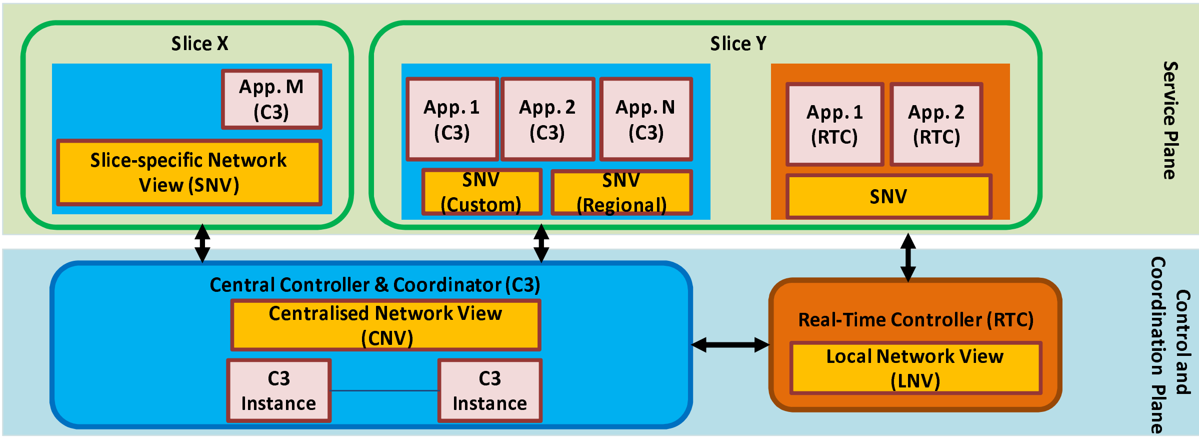

Figure 6.8: Service Network Slicing

As can be seen from Figure 6.8, each service slice includes a set of control applications running on top of either C3 or on top of RTC. Each slice can leverage on Slice-Specific Network Views (SNVs) which are derived from the centralized network view (CNV) and from the local network views (LNVs). SNVs can consist either in a subset of the information contained in the CNV and/or LNVs or they can be a slice-specific aggregation of these views.

6.4.2 Possible enhancements to Network Slicing and Slice-Specific Network View

6.4.2.1 Network slice resource management using Slice-Specific Network View

A network is realized by several resources such as radio and core network resources. In order to create several isolated logical networks in one physical network, radio resource could be associated with specific service slice. In this case, balance of the size of radio and core network resources should be stable to some extent. For example, when the amount of either resource is large enough while the amount of another resource is lower, there is redundancy within core network resource, as shown in Figure 6.9 where thickness of the cylinder represents the amount of the resource. In order to avoid this redundant resource usage and to improve the resource utilization efficiency, network slice resource management would be needed. Figure 6.10 shows the example of well-balanced resource utilization. Then, Slice-Specific Network View could contribute to the network slice resource management.

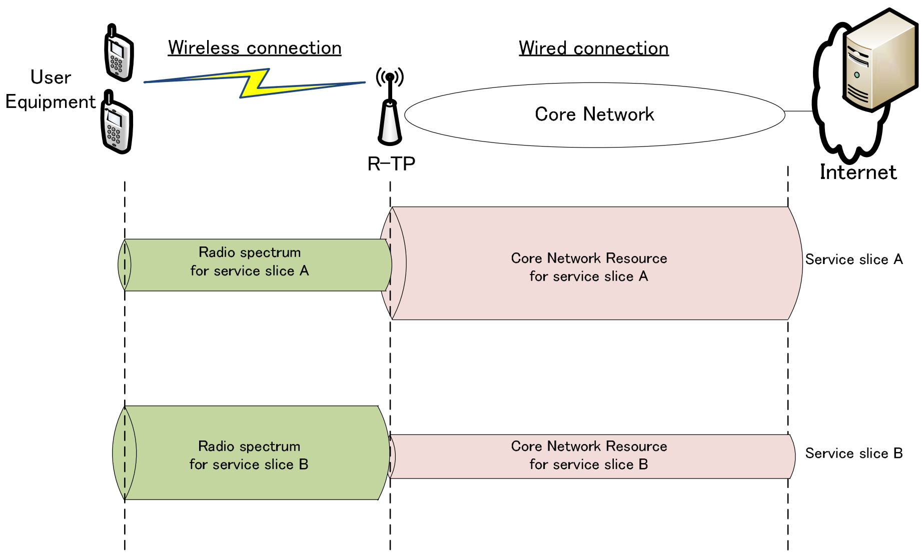

Figure 6.9: Imbalance of radio and core network resources per service slice

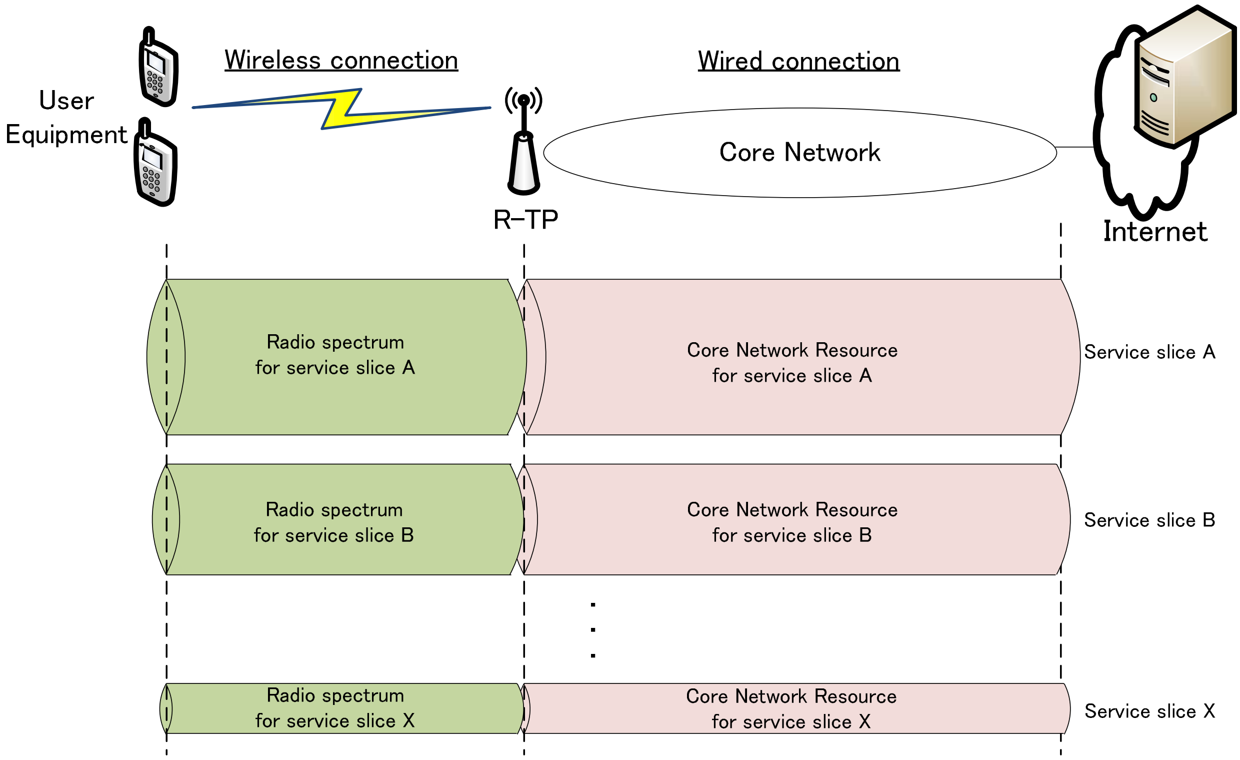

Figure 6.10: Ideal balance of radio and core network resources per service slice

7 System architecture

7.1 COHERENT architecture and functionalities

7.1.1 Overview of the COHERENT architecture

Figure 7.1 shows an overview of the general system architecture which can provide programmable control (see definition) and coordination that offers fine grain, real-time control without sacrificing scalability. Two control/coordination mechanisms namely C3 and RTC provide ***scalability*** and ***time-wise adequacy*** for control and coordination.

By receiving, through the southbound interface, status reports from lower layer entities, C3 maintains a centralized network view of the governed **entities**, e.g. transport nodes (TNs) and Radio Transceivers (RTs) in RAN. The acronym RT is referred to as a generic element in the WAS/RLAN. For example, an RT could be a legacy LTE eNBs or a legacy WiFi AP or a New Radio Base Station (NR BS).

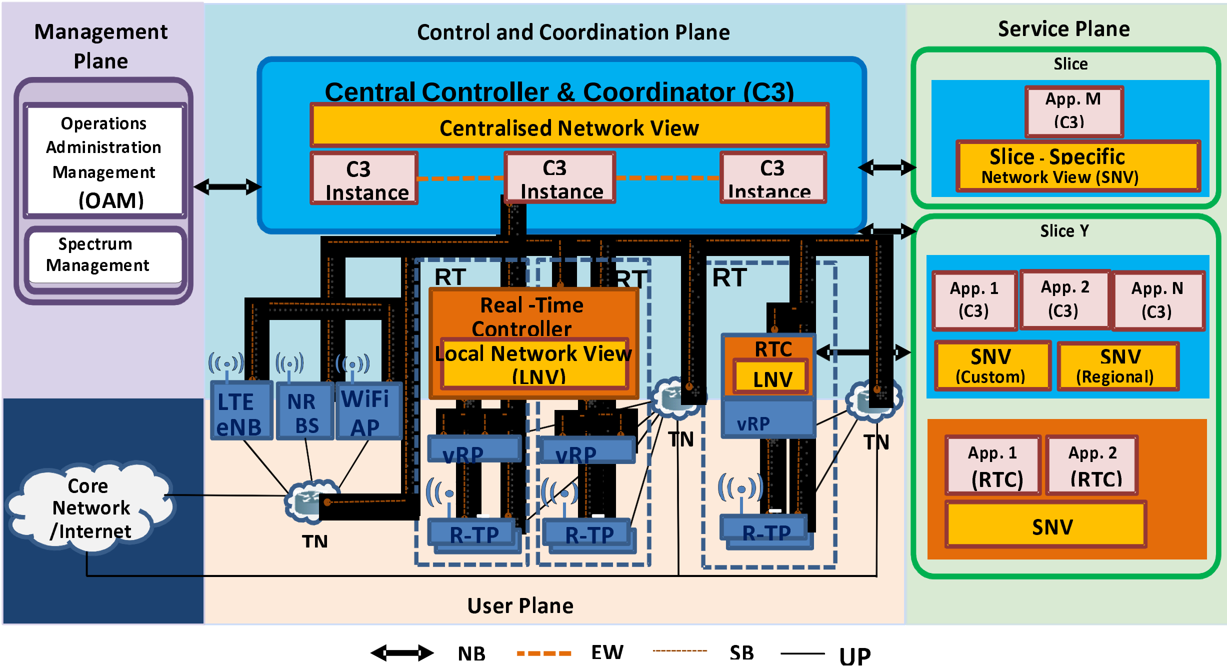

Figure 7.1: COHERENT architecture [i.1]

The network entities (TNs and RTs) connect to C3 and RTCs through the southbound interface (SBi).

A network slice in the service plane is defined as a collection of specific network applications and RAT configurations. Different network slices contain different network applications and configuration settings as shown in Figure 7.1. Through the northbound interface (NBi), C3 and/or RTCs provide the required network view, namely slice-specific network view (SNV) for the network service slices so that network service slices could express the desired network behaviours (by programming) without being responsible themselves for implementing that behaviour (with hardware).

Some application modules in network slices may be latency-sensitive. For such a slice, these modules are located in the RTC. Examples of latency-sensitive functions are RAN function splitting in 3GPP New Radio, MAC scheduling, HO decision, MAC/PHY (more generally cell) reconfiguration.

In general, different NV's could be inside the same slice, according to what the application wants to do.

While the control and coordination entities on the control and coordination plane make control decisions for RAN functions and send the decisions to the network entities for executing the decisions, the management plane usually focuses on monitoring, configuring and maintaining the long-term decisions for network entities in the infrastructure. The entities in management plane are connected to C3 through NBi.

7.1.2 Control and Coordination plane

7.1.2.1 C3 and RTC

The control and coordination plane is comprised of C3 and RTC. The main function is to orchestrate the behaviours of network entities (RTs and TNs) in the RAN so that network behaviours and RAN are harmonised. By receiving status reports from lower layer entities, C3 maintains a centralized network view (CNV) of the governed entities in the RAN.

Inside the control entities, namely C3 and RTC, there are SBi and NBi interfaces. SBi connects to different radio access technologies (RAT). Control applications are built upon the NBi interface, to perform high-level spectrum management, mobility management, traffic steering and network slicing functions. C3 will guide the lower layer control entities to implement, e.g. RAN sharing and network slicing at the RAN.

7.1.2.2 System Functionalities of RTCs and C3

7.1.2.2.1 C3 Functionalities

The functionalities of C3 are summarized as follows:

- Gather information from RTC, network and infrastructure through APIs.
- Control different parameters of different networks or infrastructure entities (Multi-RAT, switches) through APIs.
- Upgrade/Create Network Graphs among control instances.
- Control-delegation mechanisms between RTC and C3.
- Provide slice-specific network graph to network applications through API.
- Collect/coordinate configurations/policies from network applications.

7.1.2.2.2 RTC Functionalities

The functionalities of RTC are summarized as follows:

- Gather information from network and infrastructure through APIs.
- Control different parameters of different networks or infrastructure entities (Multi-RAT, switches) through APIs.
- Provide local network graph to network applications through API.
- Collect/coordinate configurations/policies from network applications.
- Control-delegation mechanisms between RTC and the network devices, e.g. eNB, vRP, R-TP.

7.1.2.2.3 Southbound API Functionalities

The functionalities of the Southbound API are summarized as follows:

- Provide transmission of relevant parameters between the controller and relevant network and infrastructure entities.
- Provide configuration of relevant network and infrastructure entities.

7.2 Possible enhancements to architecture and functionalities

7.2.1 System description

In order to support channel coordination between different network operators operating WAS/RLAN in 5 GHz bands, an interface between Coordination Managers (CMs) of different networks would be needed. Figure 7.2 shows the enhanced concept of hierarchical control. The logical architecture in Figure 7.2 also captures the use cases described in clauses 4 and the requirements described in clause 5.

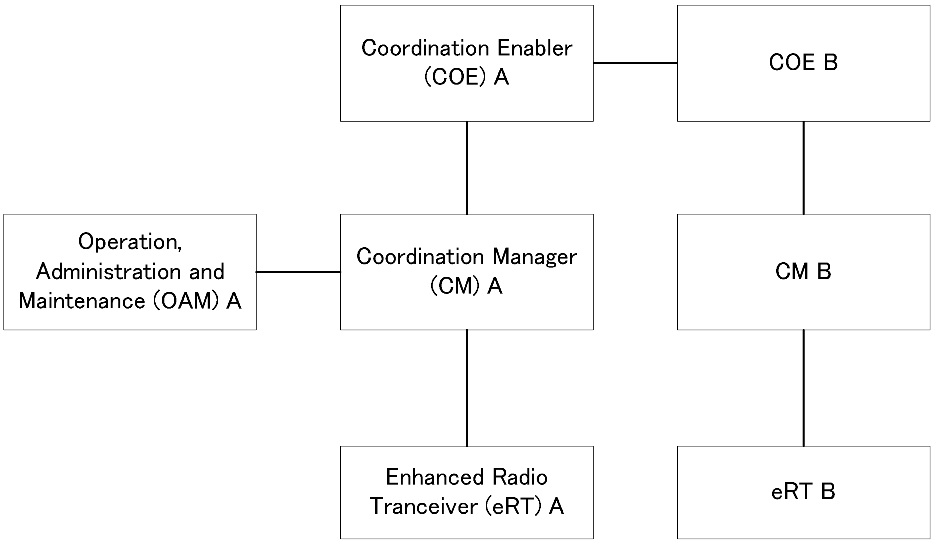

Figure 7.2: Enhanced Logical Architecture

Coordination Enabler (COE) is a logical entity that manages and determines the use of spectrum by WAS/RLANs in the same network. COE may have the following functions:

- **Coordination function:** a function to communicate with other COE within the other network. Ideally, all the information related to WAS/RLAN should be exchanged on the interface between coordination functions for global network optimization across different networks but the information related to WAS/RLAN might include the information that the network operator would not like to exchange. Then, coordination function exchanges the limited information necessary for CM at least.

- **Channel management function:** a function to determine the channel availability of each eRT in the same network and provide recommended spectrum information to CM. For the determination, COE utilizes information provided by CM. The information can include network slice setup information and eRT information.

- **Communication with Coordination Manager (CM):** a function to communicate with CM within the same network.

Coordination Manager (CM) is a logical entity which provides network-wide control/coordination for the wireless networks deployed in a given geographic area. CM may have the following functions:

- **CM instance creation function:** a function to create CM instance distributedly. CM instance can control one or more enhanced Radio Transceivers (eRT). CM instance may have capability to control one or more network slices.

- **Network slice management function:** a function to control network slice. The network slice management function can create network slice as necessarily. The network slice management function can also control the network resources for each slice. For the control, the network slice management function may utilize the information provided by Centralized Database function and COE. The information can include spectrum availability and/or operational parameters of R-TPs in eRT.

- **Centralized Database function:** a function to store the information specific to the network operation, i.e. Centralized Network View (CNV). CNV may be created by the information gathered from CM instances, network slice management function (i.e. Slice-specific Network View) and/or enhanced Real-Time Controller (eRTC) (i.e. Local Network View).

- **Communication with Management Plane:** a communication function to communicate with the entities in management plane (i.e. OAM and/or COE).

Enhanced RT (eRT) is a logical entity that provides radio access with full WAS/RLAN node functions. A set of eRTs forms a radio access network (RAN/WAS) which is coordinated and controlled by CM. Some implementation examples of eRTs include LTE eNBs in cellular networks or Wi-Fi APs in the WLANs. eRT can be realized by either of the combinations of R-TP, eVRP and/or eRTC. An eRT could be composed by one eVRP (virtual device) and one or more R-TPs (physical devices). For example, in the Cloud-RAN (C-RAN) architecture the R-TP coincides with the RRH, while the eVRP coincides with the BBU Pool. However, several other functional splits can be considered. eRT may have the following functions:

- **Enhanced Real Time Controller (eRTC):** a logical entity that is designed to offer real-time control to overcome the latency challenges. eRTCs in the WAS/RLAN may not coordinate with each other and therefore network information is not shared between eRTCs. eRTC may further have local database functionality to store the information specific to network operation, i.e. Local Network View (LNV).

- **Enhanced virtual radio processing (eVRP):** a logical entity that comprises a centralized processing of full or partial RAN node functions (including the user plane and the control plane) offloaded from one R-TP or multiple R-TPs. An eVRP includes control plane functions. An eVRP processes full or partial RAN node functions based on the information provided by eRTC or CM (or CM instance).

- **Communication with CM:** a communication function to communicate with CM within the same network. eRT can also communicate with CM instance if provided by CM.

7.2.2 Possible procedures in the enhanced architecture

In the architecture shown in clause 7.2.1, at least the following procedures would be needed.

- **Registration procedure:** Registration procedure is a procedure to register eRT information with the Hierarchical Control System. Identification information, Geolocation information and device capability information (e.g. maximum e.i.r.p, supporting frequency ranges) of eRT can be registered. The registration procedure can be done in the interfaces between CM and eRT and between OAM and CM.

- **Reconfiguration procedure:** Reconfiguration procedure is a procedure to reconfigure the operational parameters (e.g. e.i.r.p and spectrum) of eRT(s). This procedure can be performed when the CM has generated a new coexistence decision that requires reconfiguration of one or more eRTs served by this CM or when eRT asks its serving CM to reconfigure its operational parameters.

- **CM instance creation procedure:** CM instance creation procedure is a procedure to create CM instance distributedly and assign the privileges of management for radio spectrum and network slice to the CM instance.

- **COE association procedure:** COE association procedure is a procedure for COE to associate with another COE within different Hierarchical Control System.

- **eRT information exchange procedure:** eRT information exchange procedure is a procedure to obtain and/or provide the installation and/or operational parameters of eRT(s) from/to another Hierarchical Control System. This procedure can be done in the interface between CM and COE, and between two COEs.

7.3 Architecture for heterogeneous wireless access technologies

In this clause a heterogeneous system architecture is proposed, while considering that for the south-bound interface of C3 are multiple protocol candidates. The system considered by COHERENT is described in Figure 7.3. It includes the following basic elements.

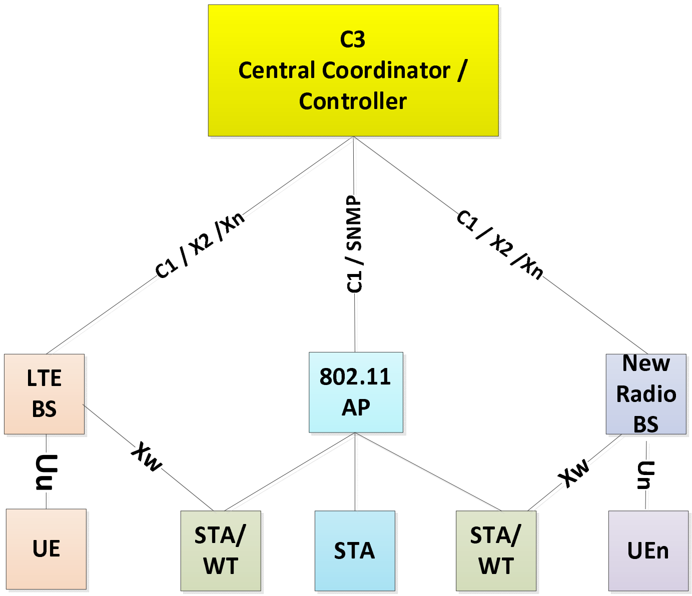

Figure 7.3: Heterogeneous architecture description

- A Central Controller/Coordinator (C3), communicating with a 3GPP base station using an X2/Xn-like protocol and with an AP using SNMP. The Central Coordinator has the role of coordinating the operation of the system, aiming to improve one or more performance indicators. Another possibility is defining a new C1 protocol for C3 communication on south-bound interface.
- A 3GPP LTE-based base station using also the shared 5 GHz spectrum. The LTE base station can use in 5 GHz a technology named LAA or can communicate with an UE through the services of WLAN Termination (WT) using IEEE 802.11 [i.8] technology.
- A 3GPP base station, using 5G New Radio technology and at least one frequency band within the 5 GHz license-exempt spectrum.
- An Access Point (AP) based on the IEEE 802.11 [i.8] technology, using at least one frequency band shared with the LTE or New Radio base station.
- An UE (User Equipment) communicating with the base station using an air protocol developed by 3GPP.
- A STA communicating with the AP using the IEEE 802.11 [i.8] protocol.
- A STA which is also a WT and delivers data to a cellular subscriber; the WT is connected to the cellular base station through a protocol Xw developed in 3GPP.

8 Measurements and reports

8.1 Measurements and reports in IEEE 802.11 standard

8.1.1 Radio measurements

8.1.1.1 Introduction

Section 4.3.8 in IEEE 802.11™-2012 [i.8], "IEEE standard for Information Technology, Local and metropolitan area networks, PART 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications" defines the general concepts related to radio measurements, targeted to improve the STA operation. The actual message formats are described in section 8 of [i.8] describing the format of the MAC frames. Over the air, any station may request another station to provide the measurement reports.

The results of the measurements are conveyed to the STA' management entity. Based on section 4.5.8 in [i.8] it is possible to retrieve the results of the radio measurements by using MLME primitives and/or MIB access.

The scope of these measurements is detailed in section 4.3.8.1 of [i.8].

8.1.1.2 Radio measurement procedures

The radio measurements in [i.8] identified as relevant to coexistence are listed below.

Beacon

The beacon request/report enables a STA to identify the APs in its neighbourhood and on a specified channel, while using the collaboration of other STAs. Details are provided in section 4.3.8.2 of [i.8].

Measurement Pilot

The Measurement Pilot frame offers a compact version of the information provided in a Beacon frame. Details are provided in section 4.3.8.3 of [i.8].

Frame

The frame request/report pair offers a representation of returns a picture of the received traffic. Details are provided in section 4.3.8.4 of [i.8].

Channel load

Details are provided in section 4.3.8.5 of [i.8].

Noise histogram

Details are provided in section 4.3.8.6 of [i.8].

STA statistics

Details are provided in section 4.3.8.7 of [i.8].

Location

Details are provided in section 4.3.8.8 of [i.8].

Measurement pause

Details are provided in section 4.3.8.9 of [i.8].

Neighbour report

Details are provided in section 4.3.8.10 of [i.8].

Link measurement

Details are provided in section 4.3.8.11 of [i.8].

Transmit stream/category measurement

Details are provided in section 4.3.8.12 of [i.8].

8.1.2 Wireless Network Management (WNM)

8.1.2.1 Introduction

The general principles of the WNM are described in section 4.3.13 of [i.8]; the standard provides an end-to-end support of the described functionality from the lower layers to the management layers. Most of the parameters are ABSTRACTED, i.e. it is reported a statistical abstraction of the measurements instead of the individual values for each measurement.

8.1.2.2 WNM procedures

Below are listed a number of procedures belonging to this service as described in [i.8].

BSS transition management

This is a procedure for infrastructure-generated handover. Details are provided in section 4.3.13.3 of [i.8].

Channel usage

This procedure assists the channel selection; details are provided in section 4.3.13.4 of [i.8].

Collocated interference reporting

Details are provided in section 4.3.13.5 of [i.8].

Event reporting

The event request and reporting procedure is detailed in section 4.3.13.8 of [i.8].

Location services

Location Configuration Request and Response procedures, enabling location-based services, are described in section 4.3.13.10 of [i.8].

Multicast diagnostic reporting

Multicast diagnostic procedures, enabling an AP to get a feedback regarding the QoS of the traffic received by a connected STA, are described in section 4.3.13.11 of [i.8].

QoS traffic capability

QoS traffic capability procedures are described in section 4.3.13.14 of [i.8].

Triggered STA statistics

The Triggered STA Statistics reporting procedures are described in section 4.3.13.16 of [i.8].

U-APSD Coexistence

The U -APSD Coexistence procedures are described in section 4.3.13.20 of [i.8].

WNM-Sleep mode

WNM-Sleep mode procedures, enabling a STA to announce when will be sleeping, are described in section 4.3.13.22 of [i.8].

8.1.3 Management procedures

8.1.3.1 Overview of IEEE 802.11 management approach

As described in section 6 of [i.8], a Small Management Entity (SME) which is internal to a station (STA) can communicate with the MAC and PHY layer management entities. However the messages between these entities are defined in a very general way such that, if supported by the station, an external Management or Control Entity can use the defined primitives.

The interaction between an SME and a station includes basic procedures such as GET and SET, to respectively receive reports and control the PHY/MAC operation.

Each procedure includes a REQUEST message and a CONFIRM message. The system information is located in a MIB (Management Information Base), having defined attributes per PHY and MAC layer.

A GET REQUEST message will specify the target attribute from the MIB, while the CONFIRM message will return the actual value of the attribute. A SET REQUEST message will provide the value of the attribute, while a SET CONFIRM message will confirm the successful setting of the attribute.

An SME can communicate with the SME of another STA; it should be noted that an AP is also a STA.

There is a policy regarding the functionality split between a SME and a layer management within a STA, i.e. the SME makes high level policy decisions (e.g. regarding measurement and channel switching), while the protocol for measurement, channel switch timing, and the execution through frame exchanges over the air belong to MLME.

8.2 MLME SAP interface

8.2.1 Introduction

The application interface for these procedures is defined in section 6.3 of [i.8].

8.2.2 Relevant procedures

Below is a list of the procedures.

Scan (section 6.3.3 in [i.8]), supporting the process of determining the characteristics of the available BSSs.

Measurement request (section 6.3.14 in [i.8]), allowing an SME to request a set of measurements to be executed and results to be provided by a peer entity.

Channel measurement (section 6.3.15 in [i.8]), allowing an SME to request measurements related to a channel, to be executed by a peer entity. The actual measurements are defined in 8.4.2.23 of [i.8].

Measurement report (section 6.3.16 in [i.8]), allowing an SME to receive the measurements related to a channel, to be provided by a peer entity. The actual measurement reports are defined in 8.4.2.24 of [i.8].

Neighbour report request (section 6.3.32 in [i.8]), allowing that a Neighbour Report Request frame be sent to the AP with which the STA is associated. Only a Radio Measurement capable STA is able to send this report.

Neighbour report response (section 6.3.33 in [i.8]), allowing to send a report response.

Link measure request (section 6.3.34 in [i.8]), allowing the measurement of link path loss and the estimation of link margin between peer entities. The transmit power to be used when transmitting the Link Measurement Request frame is defined in section 8.5.7.4 of [i.8]. The message also includes the maximum transmit power on the channel.

Location configuration request (section 8.4.2.73 of [i.8]).

Collocated interference request (section 6.3.60 in [i.8]), allows the exchange of collocated interference information between peer SMEs. The details of the request are specified respectively in section 8.5.14.13 of [i.8].

Collocated interference report (section 6.3.61 in [i.8]), allows the exchange of collocated interference information between peer SMEs. The details of the report are specified in section 8.4.2.87 of [i.8].

Channel usage request (section 6.3.66 in [i.8]), allows the exchange of information regarding channel usage between peer SMEs. The details of the request are specified respectively in section 8.4.2.88 of [i.8].

WNM - Notification request (section 6.3.69 in [i.8]), allows the exchange of WNM-Notification Request and Response frames between peer SMEs. The type of WNM-Notification Request is not defined.

WNM - Notification response (section 6.3.70 in [i.8]), allows the exchange of WNM-Notification Response between peer SMEs. The status of WNM-Notification is not defined.

8.3 Measurements in 3GPP LTE standards

The 3GPP - LTE standard 3GPP TS 36.213 [i.9] defines CQI measurements and LAA behaviour. Clause 7.2.3 describes the rules for using these measurements in LAA context. It is possible that an UE will average the CQI measurements over a number of subframes in certain conditions.

ETSI TS 136 331 [i.10] allows the programmability of the energy detection threshold. The IE named *maxEnergyDetectionThreshold* indicates the possible values in dBm with 1dBm step and starting with -85 dBm.

ETSI TS 136 214 [i.11] defines the RSSI measurements to be reported by an UE, while 3GPP TS 36.423 [i.12] defines protocols for distributed coordination between base stations. LAA is not explicitly mentioned, but this does not preclude the usage within the shared spectrum of some of the defined procedures.

8.4 Possible new reports

8.4.1 IEs for general reporting

This clause describes the new Information Elements.

Each node sends messages to C3 indicating at least one of the following information:

a) ***Received power histogram in energy detection:***

- If it is not possible to decode the transmission node ID, the listening node will just sample the received power and memorize it together with a time stamp, creating a histogram.

b) ***Release support capability:***

- A code for the supported technologies (e.g. LTE release number and type of operation, WiFi indicative of technology or 802.11 indicative of technology, for example the amendment numbers, like 802.11ac).

c) ***Power usage indication:***

- Maximum and average used transmission power per node.

d) ***DL user specific MCS log file:***

- One measurement report or a log file containing the MCS of past transmissions to specific UEs. It will include the DL transmission start time and duration.

e) ***UL user specific MCS log file:***

- One measurement report or a log file containing the MCS of past receptions from specific UEs and the start time and duration of UL received data.

f) ***UL/DL CSI/CQI/RS-SINR log file or statistical information:***

- At least one measurement or medium or maximum or minimum values or a log file containing the CSI or CQI or RS-SINR of the past receptions from specific nodes and the start time and duration of received data.

g) ***Interference power log file or statistical information in active or idle state:***

- At least one measurement or medium or maximum or minimum values or a log file containing the interference power measured on zero-power CSI-RS reference signals of past receptions or past idle state of specific nodes and the start time and duration of the measurement; missing in 3GPP only.

h) ***RSSI log file or statistical information in active or idle state:***

- At least one measurement or medium or maximum or minimum values or a log file containing the power measured as RSSI of past receptions or past idle state of specific nodes on the operating channel(s) and the start time and duration of the measurement.

i) ***RSSI log file or statistical information measured on non-operating channels:***

- At least one measurement or medium or maximum or minimum values or a log file containing the power measured as RSSI of past idle state of specific nodes on at least one non-operating channel and the start time and duration of the measurement.

j) ***Percentage of channel usage relative to the energy detection threshold:***

- The percentage of time in which each monitored channel was busy (relative to energy detection threshold or carrier sense threshold) or it was free; missing in 3GPP only.

k) ***Average and peak user throughput:***

- Average throughput and peak throughput measured per user or per node.

l) ***Delay due to congestion:***

- Delay due to congestion, i.e. due to retransmissions.

m) ***Number or percentage of discarded packets:***

- The number or the percentage of the discarded packets by a node.

n) ***Received power from other nodes as log file or statistical information:***

- Received power from other nodes either in a statistical form (average, point on CDF) or as a list of samples. Missing in 3GPP only.

o) ***Received power and the neighbour transmitting node ID:***

- Received power and the neighbour transmitting node ID (if known).

8.4.2 Reports for supporting QoS enforcement per flow or per radio bearer

Part of QoS enforcement, are envisaged reports from the nodes to C3 regarding:

a) ***Average and maximum Flow Bit Rate*** or a CDF representative value (e.g. 10 %, 90 %) for the Flow Bit Rate in the measurement interval.

b) ***Actual CW Priority level***, reflected by a priority index or the average and the minimum and maximum CW (Contention Window) used for a QoS flow.

c) ***Average and maximum flow Packet Delay*** or a CDF representative value (e.g. 10 %, 90 %) for the Average and maximum or a CDF representative value for the Packet Error rate.

d) ***Average and maximum per-transmission flow medium occupancy*** or a CDF representative value for the per-transmission flow medium occupancy.

e) ***Application type***, possibly represented by a flow ID or a PDU session ID, and if available an estimation of the duration of the active state is reported to the C3, for improving its decisions.

f) ***QoS parameters per Service Data Flow*** may include:

   1) Maximum Flow Bit Rate

   2) Guaranteed Flow Bit Rate: the bitrate (Minimum or Guaranteed bitrate per flow) that is required for the service to be delivered with sufficient QoE

   3) Priority level

   4) Packet Delay Budget

   5) Packet Error rate

   6) Admission control

The infrastructure nodes (base stations, access points) may relay or tunnel to C3 the reports of the STAs or UEs.

Such reports may include per traffic type or per a specific flow:

a) The power levels for transmission and the time-stamp of the transmission start and end.

b) The power levels measured during reception, including a time-stamp and sampled at regular intervals and presented as a file log or as representative points on a CDF.

c) The SINR during reception, including a time-stamp and sampled at regular intervals and presented as a file log or as representative points on a CDF.

d) The power levels measured during idle intervals, including a time-stamp and sampled at regular intervals and presented as a file log or as representative points on a CDF.

e) MCS (modulation and coding state) used for transmission.

f) The used LBT thresholds.

g) The used priority level reflected by the maximum CW.

h) Defer duration.

9 Control/Coordination messages

9.1 Registration to C3 and initial operation

In the centralized approach, before starting the operation, each infrastructure node (AP, base station) should listen to the environment and also register with the C3 by the set-up of a logical interface for communication.

By listening to the environment, it will be possible for a node to detect surrounding nodes and the RSSI (received signal strength indication) power. Depending on the supported technologies, for some of the nodes it will be possible to detect the surrounding node ID or Cell ID as well.

The information provided at interface set-up can include one or more information elements (IEs) containing information about:

a) Identifier of the node.

b) Node network address, for example the IP address.

c) Location name or GPS position of the node.

d) Supported standards or technologies.

e) Supported frequencies of operation.

f) Type of LBT used (energy detection, which can be with fixed threshold or variable threshold, carrier sense, which can be with fixed threshold or variable threshold, all levels being lower than the regulatory thresholds.

g) Capability of LBT per carrier in carrier aggregation, LBT level being lower than the regulatory limits.

h) Capability to modify the LBT level (energy detection level or carrier sense level) to a level lower than the regulatory limits.

i) Capability of operation related to channel width.

j) Capability of beamforming.

k) Maximum transmitted power.

l) Antenna gain.

m) Type of implementation: virtualized with multiple remote radio units, their ID, their location coordinates.

n) Operator name/ID.

o) Support of infrastructure sharing between operators.

p) Supported network slices if any.

q) Neighbor nodes ID.

r) Received RSSI from a node.

9.2 Operational performance

C3 will assess based on a trigger event or periodically the performance of the wireless network operation based on the reports received from the different nodes.

9.3 Interference coupling

If the transmitting node provides to C3, through a message, the time stamp of the transmission start and stop, and the transmission power, the C3 will request from the other nodes the reports regarding the received power during these intervals. The reports may provide the sampled power levels or a statistical representation including the average power and the power at some specific points on the CDF, for example 90 %.

Based on this information C3 may create a representation on the interference created by a node to other nodes from the same or different technologies and calculate the coupling loss between the transmitting and the other nodes.

The coupling loss, defined as the ratio between the transmitted power and the received power, will allow for example to limit the transmission power for increasing the frequency reuse factor or to request the use of a low LBT detection threshold for increasing the coverage of other node or for increasing the SINR for delivery of higher user throughput or higher probability of successful reception.

9.4 Dependency on the traffic type

Each user application may have specific requirements, for example high data rates for streaming video, low latency for V2X, high reliability for IoT.

IEEE 802.11 [i.8] uses Access Categories (AC) for establishing the minimum and maximum size of the contention window (CW) and the exponential backoff of the CW for accessing the medium. The AC is based on the QoS, derived from DiffServ DSCP.

In the existing cellular networks, such as LTE, the QoS is marked by QCI; a bearer is constructed based on QCI and the QCI values are used for establishing priorities.

In the next generation 5G networks the Service Level Agreement establishes policy rules for the transport of a traffic flow, identified by a flow ID. The policy rules may alter the priorities carried by the native DSCP marking or by the QoS requirements of the application.

In order to provide the delivery of traffic such to match both the policy rules and the native QoS requirements, it is needed that C3 is aware of the flow ID, policy rules and the native QoS for a specific traffic. A policy rule could provide the values for the maximum throughput or the maximum delay or the reliability (percentage of discarded packets), established by the network based on QoS requirements of the application.

A concept new at this time in 3GPP is the definition of PDU sessions, where each PDU session is mapped to a separate transport network bearer in order to separate them even if the contained packets have an overlapping IP address range. Also, the UE should be able to determine which IP packet belongs to which PDU session in order to route packets correctly. There may be several PDU sessions per UE.

The traffic belonging to a PDU session may be served by several technologies, for example WiFi and LTE or other cellular technology.

Based on our approach, the actual QoS parameters achieved by each used technology in transporting the data belonging to a PDU session are reported to the C3 via a message.

A PDU session could be mapped to a network slice, including a number of policy rules for resource allocation.

In our approach the policy rules are translated in radio parameters for operation in a shared band.

While the translation of the policy rules can be done locally in a distributed mode, a C3 entity having the full view of the network can make this translation in an optimal mode.

In particular, a node may request C3 through a message a change of LBT thresholds or transmitted power thresholds or delay or retransmission number or a repetition coding for itself or for the other nodes in the network, such to obtain the desired level of MCS (Modulation and Coding state) for a specific running application or a specific PDU session or a specific flow used in a PDU session. The request may include the duration of the change.

9.5 C3 actions for QoS enforcement

9.5.1 Introduction

The entities operating in 5 GHz apply the European regulations, such that the transmission power and LBT threshold are always lower than the threshold mentioned in regulations.

However, a Central Coordinator can better enforce the policy rules per flow.

Based on thereceived reports and of the requirements resulting from the QoS related to PDU sessions, flows, DSCP marking, the C3 may change the allocated frequency channels to each node and the transmission power, and/or LBT thresholds while respecting the regulatory constraints.

9.5.2 Virtual LBT

C3 may ensure that a channel is free by sending a message to the relevant nodes in which it requests that a specific channel or channels or part of a channel will not be used for a specified period of time, such to allow transmissions of nodes having delay or throughput or reliable delivery problems. This form of resource reservation was named Virtual LBT.

The virtual LBT duration can be negotiable, for example based on technical arguments or on pricing.

Virtual LBT can be used for enabling higher SNIR for selected IoT traffic, or PDU session or flow or bearer.

In this approach C3 can make available a channel for the operation of nodes using a technology by asking one or more nodes using another technology to reduce the occupancy of the channel by a given amount.

The occupancy of a channel can be expressed as the percentage of time in which a base station communicates with the associated UEs or as the percentage of time in which an AP communicates with the associated stations or as percentage of time in which stations communicate between them or as percentage of time in which UEs/STAs communicate between them.

9.5.3 Carrier aggregation and LBT thresholds

Both 802.11 and LTE use carrier aggregation; the LBT is used on each carrier separately.

C3 may set different LBT thresholds on each aggregated carrier, such that the threshold level is lower than the regulatory limits, and set the primary control channel for each UE/STA on a frequency channel selected by it. The effect of this setting is that in the presence of interference above threshold only a part of the channels will be used.

The LBT threshold selection for a component carrier in carrier aggregation may be d,ependent on the application type using that carrier, for example a broadcast application may require high coverage hence a low LBT threshold from the neighbour transmitters.

The allocation of the frequency channels to be used for transmission by different nodes can be dependent on the data rate required by the application.

If low latency and low traffic throughput is requested at one AP/BS to communicate at relatively short distance but a high latency can be accepted by the BS/APs in vicinity, the best policy is to use a channel with high LBT threshold for the application requiring low latency and high LBT and multiple channels for the neighbouring nodes. The exact allocation depends also on the scheduling policy, for example LTE can use per-carrier scheduling as a mode of carrier aggregation.

9.5.4 MCS selection

Given that C3 has a better view of the future interference, as result of the information received from the nodes and also based on its commands setting the power and LBT levels, and eventually the time-frequency resources reserved by the IEEE 802.11 [i.8] virtual carrier sense, C3 can give a more accurate prevision of the MCS to be used by the nodes in their communication with other nodes.

The MCS selection can be specific for the application, such that an application requiring low delay can be allowed by C3 a higher SINR for increasing the chances of successful reception.

10 Void

11 Examples of algorithms

11.1 Algorithm for low complexity spectrum reassignment

11.1.1 Introduction

The available spectrum for a new entrant node is determined taking into account the spectrum usage pattern of existing nodes under the constraint of protection to higher priority nodes which have higher QoS requirements. That is, the existing nodes jointly provide strong constraints to the investigated nodes in obtaining spectrum. With the wireless network operating, the released spectrum of some node maybe cannot be used by any other nodes, due to current spectrum usage limit. Consequently, the system bears dramatically increasing consumption if reassignment and reconfiguration of spectrum for all nodes occurs. This raises the need to design efficient spectrum reassignment scheme.

This algorithm presents a practical solution for reassigning the spectrum among as less nodes as possible to increase the spectrum utilization efficiency while reducing the system reconfiguration complexity. An elegant mathematical modelling is constructed, termed spectrum transition graph, to integrate all the spectrum usage information of nodes and thus generate the correlation among them. With this starting point, the connection between spectrum reassignment problem and graph theory is established. Therefore, graph theory can be used to solve the spectrum reassignment according to different system optimization targets flexibly, especially when considering hyper-dense nodes network. As an example, the following sub-clause gives the procedure of reassigning spectrum among the nodes operated by C3 through searching directed path within the relative spectrum transition graph.

11.1.2 Channel reassignment based on channel transition graph

The channel reassignment algorithm could be launched by C3 in any of the following conditions.

Condition 1: the channel released by some node cannot be assigned to the node requiring channel without bringing harmful interference to higher priority nodes or other nodes.

Condition 2: there exists a node, which cannot be assigned any channel in long time duration without harmful influence to channel usage performance, e.g. QoS, of other existing nodes.

Firstly, C3 obtains from every node the parameter, which indicates channel transition is supported by the node or not. The type of indicator parameter is BOOLEAN. If node supports the operation of channel transition, the value is set to be TRUE, and vice versa. The parameter is introduced under the following consideration: the system accommodates the widest range of nodes with a variety of architecture and QoS requirements. For example, a node could be categorized from a single communication device to a network of devices. Therefore, different nodes have different sensitive levels to the earlier than expected reconfiguration resulted by channel transition. The expected reconfiguration could be caused when the availability time period on current occupied channel expires. For a single communication device, the consumption brought by reconfiguration is probably tolerable. But a large network would suffer from dramatic performance degradation caused by signalling and operation for reconfiguration. The indicator parameter guarantees that each node is able to choose joining channel transition according to its own characteristics or requirement.

Secondly, C3 constructs channel transition graph only within the nodes that support channel transition. One example channel transition graph G is shown in Figure 11.1. Where, each vertex represents a node; any two nodes vi and vj are associated by a directed arc, depicted by (vi,vj), if and only if the protection to higher priority node can still be guaranteed when the tail vi vacates its operating channel CH_(v_i) to be used by the head vj; the corresponding channel used by tail vi, represented as CHvi, is the weight for the arc. The start vertex vs represents the node which releases a channel(s), and the end vertex ve represents the node which requires channels but cannot use the released channels directly.

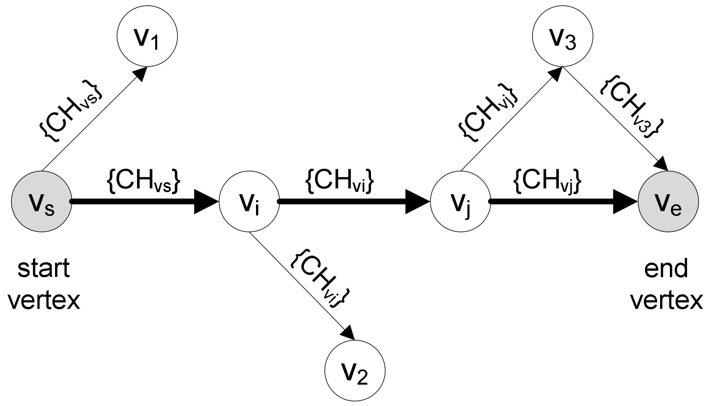

Figure 11.1: Example of channel transition graph

To determine the arc between nodes, C3 needs to obtain two more information from each considered node: available channel list and used channel list. The available channel list includes all available channels for any node and is determined according to the node's location by the Spectrum Management Database. The used spectrum list includes all spectrums which are currently occupied by the corresponding node.

Figure 11.2 shows an example of determination of arc between a pair of nodes vi and vj. Where P1 represents any higher priority node operating on the same spectrum CHvi as node vi. The left part of this figure shows the status before spectrum transition, where I(S,P1) represents the aggregated interference to P1, S denotes the set of all nodes having CHvi in their available spectrum list. I_(P_1)^th describes the maximized tolerable interference for node P1. Then, the expression of I_((S,P_1))≤I_(P_1)^th indicates the protection constraint to P1. The right part of this figure shows the supposed status after spectrum transition. If node vi vacates its CHvi to be used by node vj, then the newly aggregated interference is rewritten as I_((S∪{v_j}\\{v_i},P_1)), where the operation of S∪{v_j}\\{v_i} represents that set S includes element vj and excludes element vi. In that case, the inequality of I_((S∪{v_j}\\{v_i},P_1))≤I_(P_1)^th holds or not determines the arc (vi,vj) exists or not.

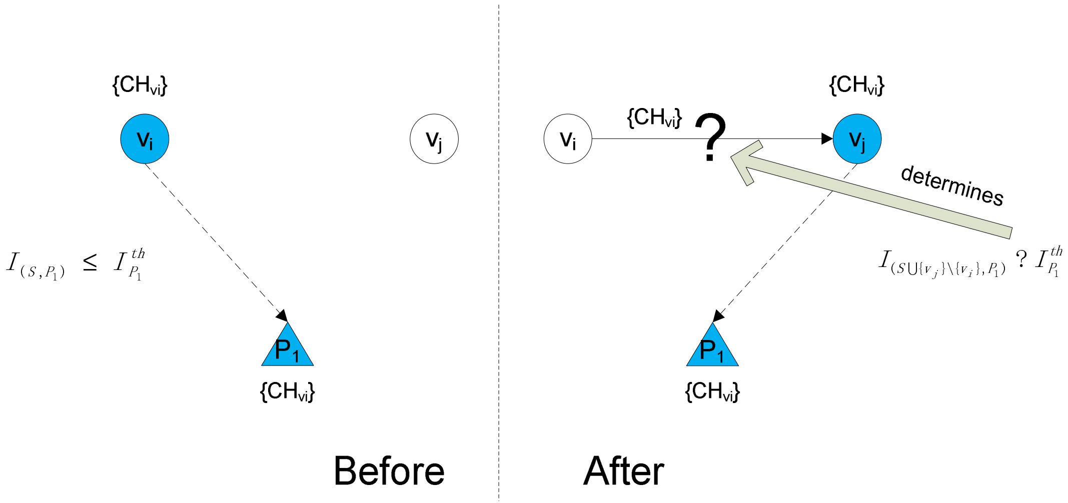

Figure 11.2: Example of determination of the arc between nodes

Based on the relation between vi's operating channel CHvi and vertex vj, C3 further classifies the node pairs into two cases, as follows.

Case 1 if the channel CHvi belongs to the available channel list of node vj but is not involved in the used channel list of vj, then the utilization of CHvi on node vj will not break protection to higher priority nodes. Therefore, an arc can be directly associated between node vi and node vj.

This can be proved briefly as follows: according to the definition of set S, the channel CHvi belongs to the available channel list of node vj means v_j∈S. That is to say S∪{v_j}\\{v_i}=S\\{v_i}. Then, it can be obtained that I_((S∪{v_j}\\{v_i},P_1))=I_((S\{v_i},P_1))≤I_((S,P_1)). Recall that I_((S,P_1))≤I_(P_1)^th. Thus, I_((S∪{v_j}\\{v_i},P_1))≤I_(P_1)^th holds.

Case 2 if the channel CHvi does not belong to available channel list of the node vj, then the influence of the newly aggregated interference to higher priority nodes cannot be deduced straightforwardly. That is to say, the relation between I_((S∪{v_j}\\{v_i},P_1)) and I_(P_1)^th cannot be got directly. Hence, recalculation of aggregated interference is required to be operated by Spectrum Management Database. With the recalculation results, C3 can determine the arcs for case 2.

Thirdly, C3 determines reassignment strategy by searching a directed path from start vertex vs to end vertex ve within the pre-generated channel transition graph. The directed path is constrained by the target performance requirements. For example, if the number of reconfigured nodes is minimized, then the directed path with shortest length starting from vs and ending at ve should be selected. In Figure 11.1, the shortest directed path from vs to ve with length of 3 as:

P(vs,ve)=(vs,vi,vj,vs) can be obtained.

C3 makes reconfiguration request based on the channel transition results and sends to corresponding node, which operates the reconfiguration accordingly.

11.2 Algorithm for channel assignment based on graph information

11.2.1 Introduction

Different nodes have different QoS requirements. When assigning channels to a node, the desired QoS should be considered in order to satisfy as many nodes as possible. Based on the geolocation information of all nodes, the distance between different nodes can be estimated. Graphs were been used commonly to describe the interference relationship among nodes. The weight of the graph edge should take into account the desired QoS of different nodes.

11.2.2 Channel assignment using graph representation of interference relationship among nodes and their expected QoS

In Figure 11.3, there are multiple nodes with different QoS requirements, which are desired SINRs. The weight of the edge is defined using the transmit power of each node Pmax and the distance dij between different nodes as well as their SINR threshold represented by SINRth. Here, i and j are the index of the nodes:

$$w_{ij} = \frac{P_{\max i} d_{ii}^{-\alpha_{ii}}}{P_{\max j} d_{ij}^{-\alpha_{ij}} SINR_{thi}} + \frac{P_{\max j} d_{jj}^{-\alpha_{jj}}}{P_{\max i} d_{ji}^{-\alpha_{ji}} SINR_{thj}}$$

The actual SINR observed at each node is represented by:

$$SINR_i = 10\lg\left(\frac{P_{\max i} d_{ii}^{-\alpha_{ii}}}{\sum_{j\in A} P_{\max j} d_{ij}^{-\alpha_{ij}} + N_0}\right)$$

where N_0 is the power of AWGN.

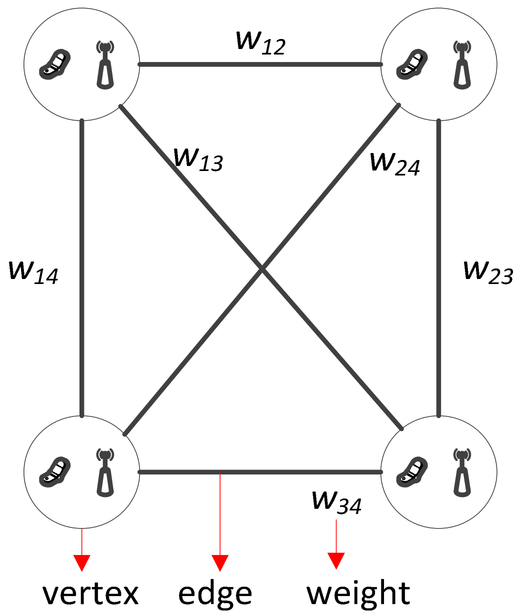

Figure 11.3: Graph representation of interference relationship among nodes

The channel assignment procedure tries to allocate as many nodes into one cluster that will be using the same channel as possible while considering the interference threshold of each individual node. The procedure is illustrated in Figure 11.4. After selecting the first node (node1), the next node (node3) is selected such that the sum of the weight of edges among the selected nodes is maximized.

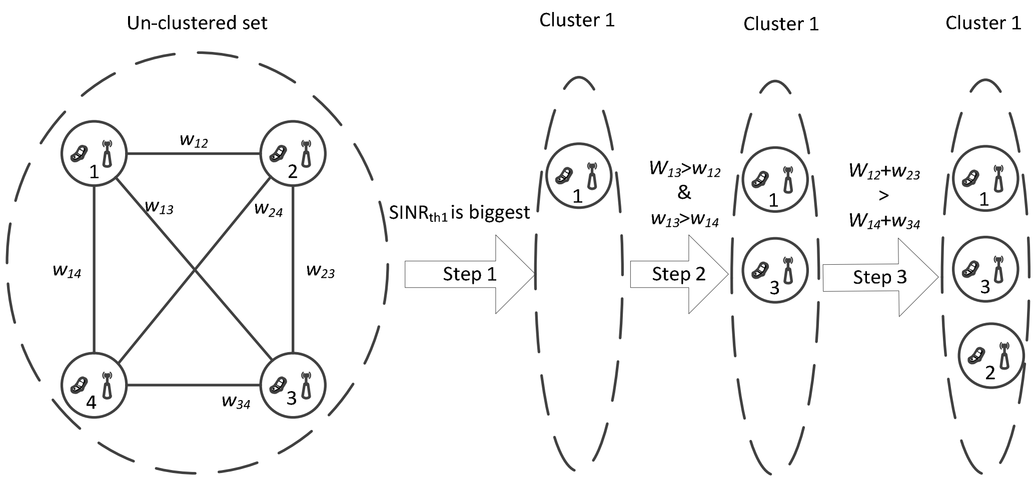

Figure 11.4: Procedure of the clustering based on graph information

Once the channel is allocated, the desired SINR should be checked among against the actual SINR observed at each node. If there is any margin between desired and actual SINRs, the transmit power of node should be reduced in order to reduce the interference among nodes as much as possible.

11.3 Algorithm for channel assignment considering interference aggregation effect at reference points

11.3.1 Introduction

When there exist more nodes, the interference power from these nodes will be accumulated. Spectrum assignment offor nodes should consider such interference aggregation effect at the reference point. The reference point can be a location where there is a node with a higher channel access priority that needs protection from the interference created by nodes with a lower channel access priority. Channel assignment considering only the interference among nodes might result in high interference level at the reference point due to the aggregation effect. This might lead to the situation where the interference margin at the reference point is reduced thus prohibiting new nodes from sharing the channel.

11.3.2 Interference aggregation effect coefficient

As shown in Figure 11.5, there are three nodes managed by two different C3s. nodes 1 and 2 are managed by C3_1 node3 is managed by C3_2. From the figure it can be seen that nodes 2 and 3 are far from each other but they are both close to the reference point 1. If channel assignment is done considering the interference among nodes, node2 and node3 will probability be assigned to the same channel. However, since they are close to reference point 1 the interference level at the reference point will be high due to the aggregation effect. Such effect is described by the channel assignment coefficient w_{ij}, for example assuming equal transmit power, as:

$$w_{ij} = \frac{1}{L_{iP_k}^{\alpha}} + \frac{1}{L_{jP_k}^{\alpha}}$$

where *i* and *j* are the index of the node, P_k is the index of the reference point and α is the pathloss exponent. *L* is the distance from the node to the reference point. The high coefficient value means a high aggregate interference effect of a pair of nodes.

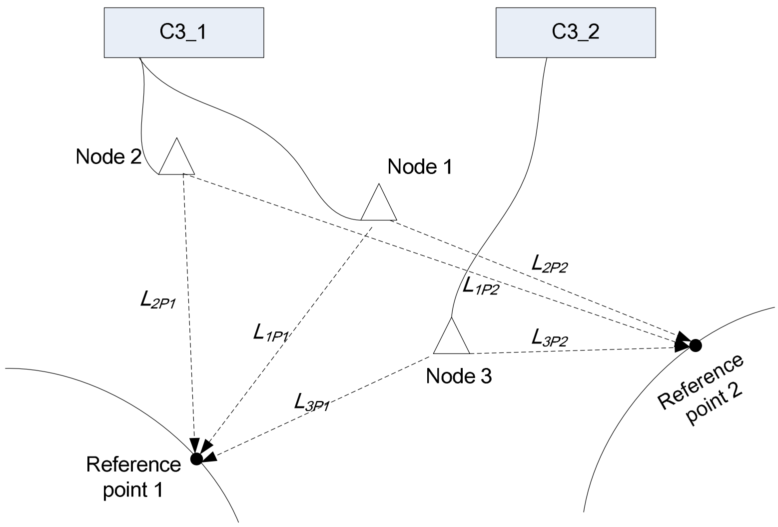

Figure 11.5: Scenario of the aggregate interference effect

In a situation of multiple C3s as shown in the figure, before one C3 chooses a particular channel for a target node from the available channels, this C3 can send the location with/without reference point information to another C3. The recipient C3 will calculate the coefficients between the target node and other nodes that are managed by the recipient C3. After that the recipient C3 will send back the coefficient for different pairs of nodes and channel utilization of the existing nodes. For example as shown in Figure 11.5, if C3_1 sends the location of node2 to C3_2, C3_2 will return w_{23} and channel utilization of node3. Then, C3_1 can opt to use same or a different channel that is used by node3 for node2 based on the value of w_{23}.

Using the coefficient in the graph based channel assignment, the coefficient can be used as the weight of the edge.

That is to say, changing the Figure 11.3 of clause 11.2.2 by replacing the edge-weight to be the coefficient as defined in this proposal, a new weighted graph is obtained. Given the channel utilization information of the existing nodes and the channel assignment coefficient, the channel assignment will result in allocating different channels to a pair of nodes that have a high coefficient. Such procedure will reduce the aggregate interference level at the reference points. Thus, when accommodating new nodes the information exchange between C3s for adjusting existing nodes is reduced.

11.4 Algorithm for the selection of candidate serving C3 instances for moving nodes

11.4.1 Introduction

Figure 11.6 shows an example where candidate serving C3 instances selection based on mobility information of moving node of WAS/RLAN can be considered. In this example, a moving node N_1 is supposed to associate with its current serving C3 instance CI_0 and move along the route R, depicted by a red line. The candidate serving C3 instances for the moving node N_1 comprise of a set of C3 instances along the predicted route R, which can satisfy N_1's requirements on available spectrum and residency duration while guaranteeing service continuity for N_1.

Having the information of candidate serving C3 instances enables a moving node to efficiently select a C3 instance as its serving C3 instance which can provide better spectrum environment to co-locate with other nodes without harmful interference. That is to say, such information helps a moving node to avoid interaction consumed to associate with the C3 instances which cannot satisfy the moving node's requirement. On the other hand, the information of candidate served nodes is also beneficial for a C3 instance to provide efficient network coordination. This algorithm designs a way to select and provide the information of candidate serving C3 instances to moving nodes. The information of candidate serving C3 instances can be updated at least as often as the mobility information update from the moving node to its current serving C3 instance. This algorithm can also be utilized in the context of Coordination Manager (CM) where the CM instance operates as controller for moving node of WAS/RLAN. For the sake of simplicity, the following subclause only employ C3 instance as an example controller to illustrate this algorithm, while candidate serving CM instances can be selected alike.

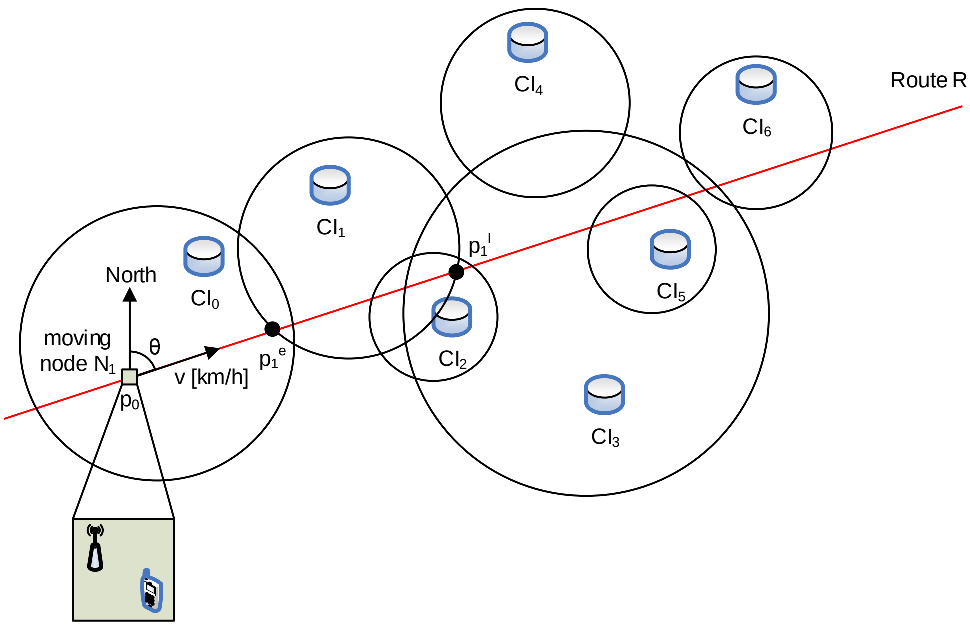

Figure 11.6: Example case of candidate serving C3 instances selection for moving node of WAS/RLAN

11.4.2 Selection of candidate serving C3 instances for moving nodes

In Figure 11.6, N_1 is moving from the position of p_0 at time T_0 with a direction angle of θ degree (against longitude facing North in clockwise direction) and a speed of v [km/h]. Current serving C3 instance of N_1 is CI_0. There exist six C3 instances ahead, denoted by CI_i, $i \in [1..6]$, close to the route R. For simplicity, it is assumed that the serving area of each C3 instance is a circle. For each CI_i whose serving area is crossed by the route R, its serving area border has two intersection points with the route R: p_i^e denotes the first point for N_1 to enter the serving area of CI_i, p_i^l denotes the last point for N_1 to leave the serving area of CI_i.

Without the information of candidate serving C3 instances on the route R, N_1 has to estimate C3 instances one by one along the route R when moving close to the serving area of C3 instances in sequence of CI_1, CI_2, CI_3, CI_4, CI_5 and CI_6. Wherein, after association with CI_2, N_1 may change to be served by CI_3 immediately. Similarly, after association with CI_5, N_1 may change back to be served by CI_3. Contrarily, if having the information of candidate serving C3 instances prior to its move, N_1 is able to efficiently select its serving C3 instance at each location. Also for each C3 instance, knowing the information of moving nodes enables the C3 instance to deduce its served nodes that might be impacted by the moving nodes and therefore make better planning for spectrum assignment.

In this algorithm, the following three processes are conducted.

1) Identify initial serving C3 instances of a moving node based on the mobility information of the moving node and the serving area information of other C3 instances along the predicted route:

   - A set of initial serving C3 instances is formed by the C3 instances whose serving area is crossed by the predicted route R of a moving node. The route R can be predicted based on speed/direction in mobility information of the moving node. If the route information is also provided in the mobility information, the route R can be predicted more precisely. Through information sharing among C3 instances, current serving CI_0 of N_1 can obtain the serving area information of other C3 instances. By utilizing the serving area information, CI_0 identifies for N_1 the initial serving C3 instances that satisfy the condition to be initial. In Figure 11.6, the set of initial serving C3 instances comprises of CI_1, CI_2, CI_3, CI_5 and CI_6. Besides, CI_0 estimates the arrival time of N_1 at the serving area of each CI_i as $T_i^a=T_0+ D(p_i^e, p_i^l)/v$, and the residency duration of N_1 within the serving area of each CI_i as $T_i^r=T_0+D(p_i^e, p_i^l)/v$, where $D(p_1, p_2)$ is the distance between two points p_1 and p_2.

2) Determine selection priority level of the initial serving C3 instances based on their estimated available spectrum for the moving node:

   - CI_0 requests information on estimated available spectrum for N_1 from the initial serving C3 instances. The request includes estimated arrival time T_i^a at p_i^e, residency duration T_i^r within CI_i, and desired resource requirement (e.g. bandwidth). Upon receiving request, each CI_i estimates its available spectrum for the investigated moving node and responds to CI_0. Then based on the estimated available spectrum, CI_0 labels the initial serving C3 instances with a selection priority level, denoted by L_i. The larger the amount of estimated available spectrum can be provided, the higher the selection priority level is.

3) Select candidate serving C3 instances for the moving node from the initial serving C3 instances:

   - One method to select the candidate serving C3 instances for a moving node with requirement is modeling the relation among the initial serving C3 instances by utilizing an association graph.

   - Figure 11.7 shows an example association graph G corresponding to the case in Figure 11.6. Each control vertex v_i represents an initial serving C3 instance CI_i. Directed arc, depicted by (v_i,v_j), represents that serving area of the corresponding two C3 instances are overlapped on the route R and the moving node is supposed to move from the serving area of tail v_i to that of head v_j. Each v_i has the estimated residency duration T_i^r as a first weight and the selection priority level L_i as a second weight. In this figure, v_1 and v_6 are labeled as start vertex and end vertex, respectively.

   - The candidate serving C3 instances can be obtained by searching a directed path from start vertex v_1 to end vertex v_6 in graph G. For example, if to minimize the number of C3 instances on the route, the directed path with shortest length from start vertex to end vertex should be selected. During the searching, CI_0 places a higher priority on the C3 instance which has longer residency duration T^r_i and higher selection priority level L_i. Consequently, less interaction for association and more spectrums for the moving node could be achieved.

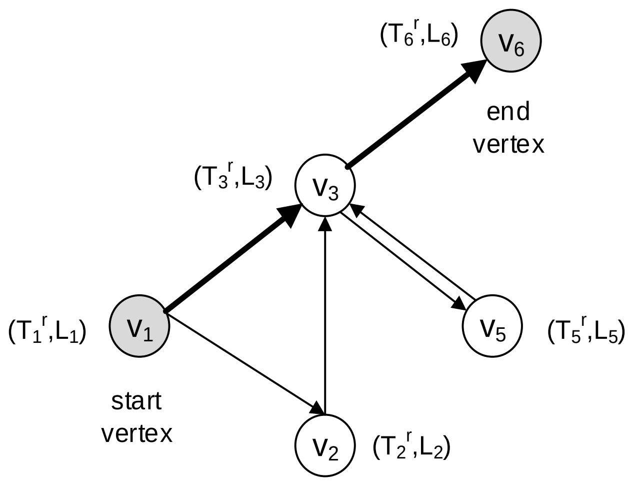

Figure 11.7: Example of association graph G

In Figure 11.7, the shortest directed path from v_1 to v_6 is with length of 2 as: $P(v_1,v_6)=(v_1,v_3,v_6)$. If the residency duration T_i^r of these three C3 instances is long enough, and the selection priority level L_i of these three C3 instances can satisfy N_1's requirement, then these C3 instances can be selected as the set of candidate serving C3 instances for N_1. CI_0 can provide the results also to the candidate serving C3 instances. For the candidate serving C3 instances, this information helps to make better planning for their spectrum assignment accordingly.

11.5 Algorithm for network coordination based on spectrum utilization pattern

11.5.1 Introduction

This algorithm presents a network coordination scheme that ranks channels for the nodes of WAS/RLAN based on their spectrum utilization pattern. The spectrum utilization pattern captures the behavioural pattern on the spectrum usage of the nodes. The following clause describes the definition and estimation of the spectrum utilization pattern. At the last clause, channel assignment algorithm using such concept is introduced.

11.5.2 Spectrum utilization pattern

The parameter of spectrum utilization pattern is defined as a distribution of spectrum usage within a fixed interval of time and/or space. The spectrum usage events can be categorized into successful usage and failed usage. Successful usage of a spectrum for a certain node is defined as that the desired QoS (e.g. expected packet error rate) is guaranteed and the communication lasts over a predefined time interval and/or in a given area. Otherwise, it is deemed as a failed usage.

Figure 11.8 shows an example use case where spectrum utilization pattern should be considered in network coordination. In the example, a set of nodes n_1, n_2, n_3 and n_4 distribute stably around an area A. There are two available channels CH_1 and CH_2, where CH_1 is used by n_1, n_3 and n_4, while CH_2 is used by n_2. Assume a new entrant node n_a appears (or moves) into the target area A. Before introducing spectrum utilization pattern, only operational channel sequence $\{CH_1, CH_2\}$ is indicated to n_a. In that case, it is probably for n_a to utilize CH_1 firstly and thus suffering from lower spectrum efficiency before switching to CH_2. After introducing spectrum utilization pattern, C3 instance can indicate to n_a the recommended channel utilization order in the form of a sequence of operating channels sorted in decreasing order of utilization efficiency as (CH_2, CH_1). When receiving such ordered sequence, n_a can select the CH_2 to use from the beginning and thus achieving high spectrum efficiency.

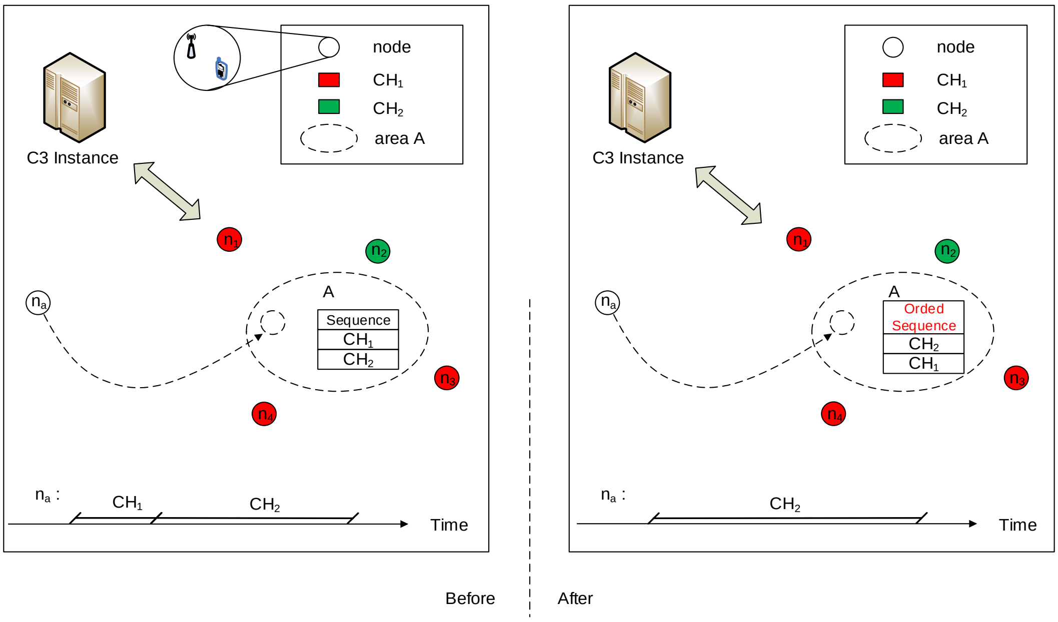

Figure 11.8: Example use case of spectrum utilization pattern

The parameter of spectrum utilization pattern can be expressed in a variety of way. For instance, denote the event of spectrum usage, successful usage and failed usage by $\mathcal{U}$, $\mathcal{S}$ and $\mathcal{F}$, respectively. Define random variables as the number of spectrum usage, successful usage and failed usage events, denoted by $N_{\mathcal{U}}$, $N_{\mathcal{S}}$ and $N_{\mathcal{F}}$, respectively. Then, the distribution can be expressed, for example, by mean or standard deviation of $N_{\mathcal{U}}$, $N_{\mathcal{S}}$ or $N_{\mathcal{F}}$ per unit time and/or per unit space.

In Figure 11.9, an example distribution of spectrum usage events on CH_1 for node n_a is illustrated. Estimation window representing the time interval for the distribution estimation is determined by a start time of $T_{WinStart}$ and a stop time of $T_{WinStop}$. A threshold of time duration for successful usage on CH_1 is denoted by T_1^{th}. Three spectrum usage events on CH_1 distribute within the window, with time duration of T_1^1, T_1^2 and T_1^3, respectively. Compared with the threshold T_1^{th}, T_1^1 and T_1^3 are successful usage, whereas T_1^2 is a failed one. Then, $N_{\mathcal{U}} = 3$, $N_{\mathcal{S}} = 2$, and $N_{\mathcal{F}} = 1$ are obtained for the estimation window. And the number of every event per unit time can be obtained through dividing $N_{\mathcal{U}}$, $N_{\mathcal{S}}$ or $N_{\mathcal{F}}$ by the duration of estimation window, i.e. $T_{WinStop}$ - $T_{WinStart}$.

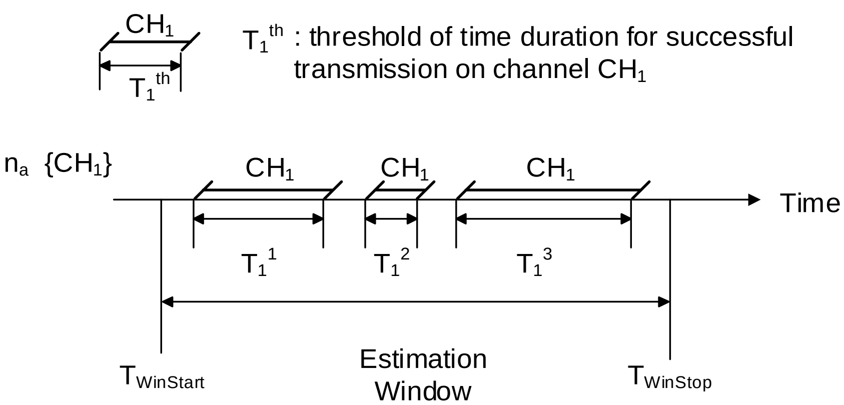

Figure 11.9: Example of distribution of spectrum usage event

11.5.3 Channel ranking methodology based on spectrum utilization pattern

Channels to be utilized by a new entrant node can be ranked based on the spectrum utilization pattern in the target area where the new entrant node operates. In the channel ranking process of this algorithm, high efficiently utilized channel is ranked at the top, where the interference constraints among nodes are also guaranteed.

After receiving the spectrum utilization information for the target area, C3 instance can initiate the channel ranking based on spectrum utilization information. The channel ranking process includes the following steps:

1) Modelling the nodes by weighted interference digraph based on prospective interference level among nodes.

2) Sorting the channels and nodes in the digraph based on the spectrum utilization pattern.

3) Abstracting the channel ranking result.

For step 1, prospective interference level among nodes is calculated, and then weighted interference digraph is derived. One example of weighted interference digraph G is shown in Figure 11.10, where Figure 11.10(a) shows the scenario of nodes distribution and Figure 11.10(b) shows the generated digraph for the scenario. In the digraph, each vertex represents a node. An arc indicates that the prospective interference level from tail to head, denoted by $I_{(tail,\ head)}$, exceeds a predefined threshold. The prospective interference level is labelled as weight on corresponding arc. The operational channels of each node are treated as weight for corresponding vertex. Moreover, spectrum utilization pattern information is in connection with the associated operational channel. Based on modelling the system with weighted interference digraph, graph theory can be utilized to solve the channel assignment among the involved nodes.

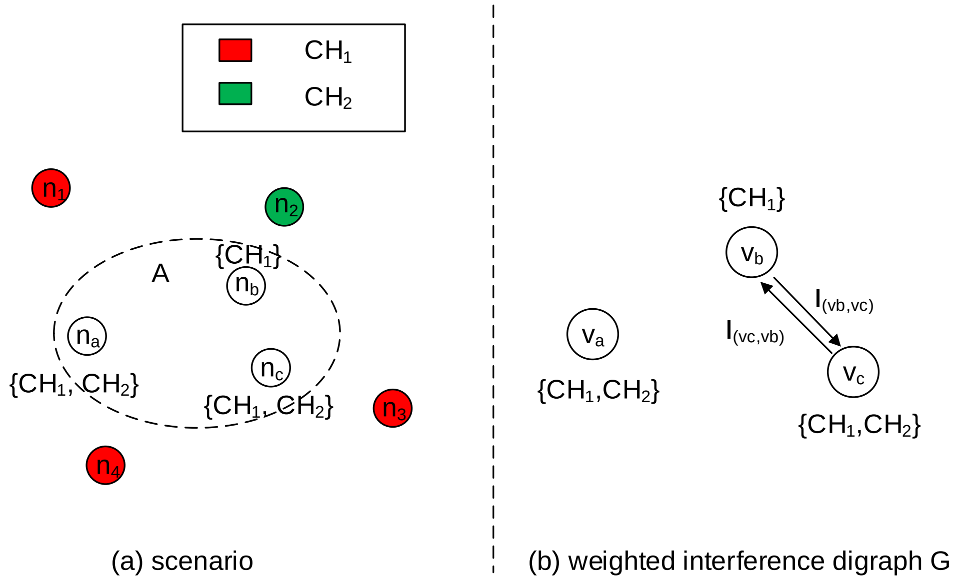

Figure 11.10: Example of weighted interference digraph

For step 2, a coloring algorithm is designed. Firstly, the channels and nodes in the digraph G are sorted in some ordered sequence. Then estimate each channel along the channel sequence. For each channel, estimate along the node sequence to see if each node can be added to a vertex set within which all nodes can simultaneously use the identical operational channel while satisfying interference constraints among the nodes. In sorting the channels and nodes, the following rules are adopted:

a) The high-efficiently utilized channel should be treated as higher rank than the other channels.

b) The node utilizing channel high-efficiently should be treated as higher rank than the other nodes.

In these rules, the utilization efficiency is represented by the ratio of the number of successful usage events per time unit to the number of spectrum usage events per time unit. The higher the value of the utilization efficiency, the more efficiently the channel is used. Assume, in Figure 11.10(b), the channels are sorted as (CH_2, CH_1). For CH_2, the nodes are sorted as (v_a, v_c). For CH_1, the nodes are sorted as (v_b, v_a, v_c). Then, for CH_2, estimate each vertex to generate a sorted set of (v_a, v_c); for CH_1, estimate each vertex to yield a sorted set of (v_b, v_a). The result in this process is illustrated in Figure 11.11(a), where each row includes the vertices using the identical channel as labeled; the rows are listed based on the labeled channel in decreasing order of utilization efficiency from top to bottom; and in each row the vertices are sorted in decreasing order of utilization efficiency on the used channel from left to right.

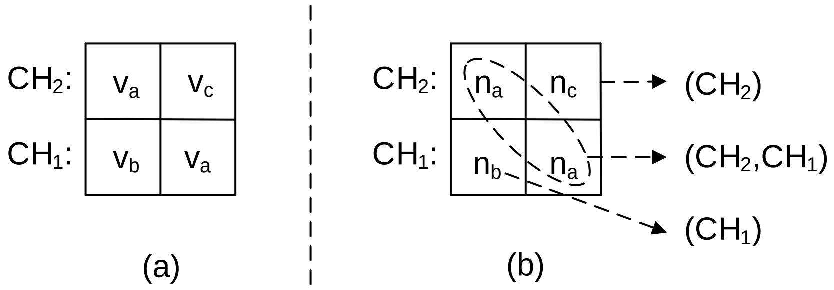

Figure 11.11: Example of channel ranking result

During the sorting process, each node is sequentially assigned to different vertex set associated with different assigned channel. Then, for step 3, a ranking result within operational channel list for each node is abstracted accordingly.

For example, in Figure 11.11(b), n_a has been assigned to the vertex set in the sequence associated with (CH_2, CH_1). Then, as illustrated in Figure 11.11(b), the ordered channel sequence (CH_2, CH_1) is assigned to n_a. Likewise, (CH_1) is assigned to n_b and (CH_2) is assigned to n_c.

Annex A:
Change History

Date	Version	Information about changes
March 2017	0.0.1	Initial draft.
April 2017	0.0.2	Added definitions, replaced RAN with WAS/RLAN, added section 4.3.3.
July 2017	0.0.3	Added text and changes from contributions BRAN(17)000040,41.
August 2017	0.0.4	Added text and changes from contributions BRAN(17)000041r1, BRAN(17)000060r1, BRAN(17)000063r1, BRAN(17)000064r1, BRAN(17)000065, BRAN(17)000066r1, BRAN(17)000067r2, BRAN(17)000068r1, BRAN(17)000071r1 and BRAN(17)000072r1.
November 2017	0.0.5	Added text and changes from contributions BRAN(17)000069r2, BRAN(17)000070r2, BRAN(17)000095r1, BRAN(17)000097r2, BRAN(17)000098r1, BRAN(17)000099r2 and BRAN(17)000100r2. Implemented the agreements on replacing “spectrum” with “channel” as instructed in the minutes of BRAN#95.
November 2017	0.0.6	Mainly addressed the editHelp comments and changes.
December 2017	0.0.7	Added text in Introduction section to reflect comments during BRAN#96.
December 2017	0.0.8	Clean version of the previous draft for TC BRAN approval.

History

Document history		
V1.1.1	January 2018	Publication