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DECT-2020 NR CONFORMANCE TESTING

Testing for MAC layer

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TIIVISTELMÄ

Tuomas Pirilä: DECT-2020 NR vaatimustenmukaisuuden testaus MAC-protokollakerroksella
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Ennen tuotteen laskemista EU:n markkinoille on sen valmistajan varmistettava, että tuote täyttää sille asetetut vaatimukset. Tämä varmistetaan vaatimustenmukaisuuden arvioinnilla, jossa tuotetta testataan siihen liittyvien standardien määrittelemällä tavalla tai niiden vaatimuksia vastaan. Tämä työ keskittyy radioprotokollastandardin testaukseen.

Syy miksi radiolaitteita testataan ensisijaisesti, on se, että lopullinen tuote saisi todellista käyttöä. Vaatimukset radiolaitteille Euroopan talousalueella tulevat radiolaitedirektiivistä, joka säätelee niiden käyttöä ja myyntiä. EU tukee jäsenmaitaan direktiivien tavoitteiden saavuttamisessa yhdenmukaistetuilla standardeilla.

Testausta tulee myös tehdä standardissa määriteltyjen vaatimuksien noudattamiseksi. Standardien vaatimukset sisältävät yksityiskohtaisesti määriteltyjä sääntöjä ja tapoja, miten kyseisen standardin toteuttavien radiolaitteiden tulee kommunikoida ja käyttäytyä. Yhteisen standardin noudattaminen kaikissa toteutuksissa parantaa tuotteiden laatua ja mahdollistaa yhteensopivat toteutukset eri valmistajien välillä.

Teknologia, jolle tämän työn testaus on tarkoitettu, on DECT-2020 NR -radiotekniikka, joka on suunniteltu suuren skaalan IoT:n käyttötarkoituksiin, kuten älymittareita tai älyvalaistusta varten. Näitä käyttötarkoituksia voidaan toteuttaa DECT-2020 NR:n tuoman mesh-teknologian avulla. Fyysisellä kerroksella DECT-2020 NR on CP-OFDM-pohjainen tukiasematon radiotekniikka, joka toimii 1900 MHz:n lisenssivapaalla radiokaistalla, joka on alun perin tarkoitettu alkuperäisen DECT radiojärjestelmän käyttöön. DECT-2020 NR operoi vanhan DECT:n rinnalla käyttämällä mm. spektrintunnistusmenetelmiä häiriöiden välttämiseksi.

Tässä työssä testattiin DECT-2020 NR radiotekniikan toteuttavaa tuotetta ETSI EN 301 406-2 yhdenmukaistetussa standardissa määriteltyjen testausmenetelmien avulla. Työssä esiteltiin, millaisia tuloksia täytyy saada, jotta tuote voidaan todeta olevan yhdenmukaistetun standardin ja siten myös radiolaitedirektiivin siihen liittyvän vaatimuksen mukainen. Testaus kohdistettiin kanavapääsytesteihin satunnaispääsymenetelmällä, jonka toiminnallisuuden tarjoaa MAC-protokollakerros.

Kyseiseen yhdenmukaistettuun standardiin ei tämän työn kirjoitushetkellä oltu vielä viitattu Euroopan Unionin virallisessa lehdessä. ETSI on kuitenkin julkaissut kyseisen standardin radiolaitedirektiivin mukaisesti elokuussa 2023, joten listaus edellä mainittuun lehteen tulee tapahtumaan lähitulevaisuudessa, jonka jälkeen sitä voidaan käyttää lainsäädännöllisenä todisteena vaatimustenmukaisuudesta. Tätä ennen arvioinnin voi aina suorittaa ilmoitettu laitos.

Koska DECT-2020 NR on vielä melko uusi standardi, sille ei ole vielä määritelty standardisoituja testejä. Tässä työssä määriteltiin alustavia testitarkoituksia standardisoitavaan vaatimustenmukaisuuden testaukseen. Testit johdettiin suoraan standardin määrittelystä keskittyen MAC-protokollakerrokseen.

Testimäärittelyiden lisäksi tässä työssä esiteltiin myös esimerkkejä standardinmukaisuuden osoittamisesta tarkastelemalla systeemisimulaatiosta saatuja pakettikaappauksia hyödyntäen verkkoprotokollien analysointityökalua, jossa sanomien sekvenssejä ja bittisisältöä voidaan tarkastella. Toisena vaihtoehtona työssä esitetään vaatimustenmukaisuuden testijärjestelmiä hyödyntäen RF-mittalaitteistoa, joka havaittiin käytännölliseksi vain vähään määrään testejä.

Kokonaisuudessaan työ osoittautui kokeelliseksi tutkimukseksi vielä kehitteillä olevan, uuden radiotekniikan standardisoidusta ja lainsäädännöllisten vaatimuksien mukaisesta testauksesta, samalla esittäen esimerkkejä miten varhaisia toteutuksia pystytään testaamaan.

Avainsanat: DECT-2020 NR, Vaatimustenmukaisuuden arviointi, Yhdenmukaistettu standardi, Kanavapääsy, Radiolaitedirektiivi, Wireshark.

ABSTRACT

Tuomas Pirilä: DECT-2020 NR conformance testing; Testing for MAC layer
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Before placing any products on the EU market, a manufacturer must ensure that its products comply with essential requirements. To ensure that a product complies with its requirements, a conformity assessment is carried out, where the product is tested according to the methods or against the requirements defined in the related standards. This thesis concentrates on testing of a radio protocol standard.

The reason why testing for radio equipment is done in the first place is for the final product to get real use in the world. The requirements for radio equipment in the European economic area come from the Radio Equipment Directive which regulates the use of radio devices and their marketing. The EU supports its members to fulfil the objectives of the directive by providing harmonised standards.

Secondly, testing should also be done to conform with the relevant requirements specified in the standard specifications. These specifications provide detailed rules and procedures on how the radio devices implementing the standard should communicate and behave. Having a common standard as a baseline for all implementations raises the quality, and most importantly enables the interoperability of implementations between manufacturers.

The technology for which the testing in this thesis is intended is the DECT-2020 NR radio technology, designed for massive-scale IoT having applications such as smart metering, lightning etc, capable of being implemented by utilizing its mesh operation mode. On the physical layer, the DECT-2020 NR is a CP-OFDM-based non-cellular radio technology operating on the 1900 MHz licence-exempt band originally intended for the use of the legacy DECT, by co-existing with it by deploying autonomous spectrum sensing capabilities for interference avoidance.

This thesis tested a product implementation of DECT-2020 NR according to the test methods defined in the ETSI EN 301 406-2 harmonised standard. The thesis shows what kind of results shall be obtained for a product to conform with the requirements of the harmonised standard and thus with the related requirement of the directive. The testing was focused on the channel access tests in a random-access manner, where the functionality is provided by the MAC protocol layer.

At the time of writing this thesis, the harmonised standard has not yet been referenced in the official journal of the European Union. However, ETSI released the harmonised standard under the Radio Equipment Directive in August 2023, meaning that listing to the OJEU will happen in the near future, after which it is allowed to be used as a direct proof of compliance with the directive. Before this, a notified body may always perform the conformity assessment.

As the DECT-2020 NR radio technology is a relatively new standard, there are no standardised test specifications available. In this thesis, an initial set of test purposes for the use of the conformance specification were defined. The test purposes were derived directly from the core specification focusing on the MAC layer procedures.

In addition to defining test purposes, this thesis also showed examples of proving conformity with the standard by using packet captures acquired from system simulations and inspecting them by using a network protocol analysing tool, where the message sequences and their internal bit content could be inspected for defining a test verdict. As another option, physical test setups using RF measurement equipment were used for the purpose of conformance testing, although found to be usable only for a limited set of features.

In conclusion, the thesis has turned out to be a study of standardised and regulatory testing of a new radio technology which is still under development, while showing examples of how the testing for an early implementation may be done.

Keywords: DECT-2020 NR, Conformance testing, Harmonised Standard, Radio Equipment Directive, Channel-access, Test purposes, Wireshark

PREFACE

This thesis was done for Wirepas Ltd between September 2023 and May 2024.

For a couple of years now, I have been involved in DECT-2020 NR related activities, starting from simulations on the physical layer and moving on to standardisation and testing the upper protocol layers. It has been a great advantage that I have been able to write this thesis focused on a technology previously familiar to me, while also bringing new challenges in the field of regulations, and standardisation.

It has been fascinating to work with an actual product implementation of the DECT-2020 NR radio technology while also being able to utilise the skills and knowledge from previous work experience and university studies in practice.

I hope that this thesis might someday even prove useful for someone trying to figure out what conformance testing is and how it could be done, especially when needing to prove compliance with the DECT-2020 NR harmonised standard.

I would like to thank Juho Pirskanen for giving me this opportunity and all the colleagues working on the regulatory testing part of this thesis. Special thanks also go to my friends and family for being supportive throughout the work and my university studies.

Tampere, 17.05.2024

Tuomas Pirilä

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ABBREVIATIONS

3GPP	3^{rd} Generation Partnership Project
ACK	Acknowledgement
AWGN	Additive White Gaussian Noise
BCC	Broadcast Control
BLER	Block Error Rate
BSC	Beacon Scanning Control
CAB	Conformity Assessment Body
CCC	Connection Configuration Control
CE	Conformité européenne (Engl. European conformity)
CEN	Comité Européen de Normalisation (Engl. European Committee for Standardisation)
CENELEC	Comité Européen de Normalisation Électrotechnique (Engl. European Committee for Electrotechnical Standardisation)
CEPT	Conférence européenne des administrations des postes et des télécommunications (Engl. European Conference of Postal and Telecommunications Administrations)
CQI	Channel Quality Indicator
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
CVG	Convergence (layer)
DECT-2020 NR	Digital Enhanced Cordless Telecommunications 2020 New Radio
DLC	Data Link Control (layer)
ECC	European Communications Committee
EEA	European Economic Area
EFTA	European Free Trade Association
EMCD	Electromagnetic Compatibility Directive
EU	European Union
EUT	Equipment Under Testing
ETSI	European Telecommunications Standardisation Institute
FT	Fixed Termination (Operating mode)
GPIO	General Purpose I/O
HARQ	Hybrid Automatic Repeat Request
IE	Information Element
IoT	Internet of Things
IUT	Implementation Under Testing
ITU-R	International Telecommunications Union – Radiocommunication Sector
LBT	Listen Before Talk
LRC	Local Radio Control
LTE	Long Term Evolution (4G)
LVD	Low Voltage Directive
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MRA	Mutual Recognition Agreement
NACK	Negative Acknowledgement
OJEU	Official Journal of the European Union
PCC	Physical Control Channel
PCO	Point of Control and Observation
PDC	Physical Data Channel
PDU	Protocol Data Unit
PICS	Protocol Implementation Conformance Statement
PT	Portable Termination (Operating mode)
PTC	Paging Transmission Control

QoS	Quality of Service
RAC	Random Access Control
RACH	Random Access Channel
RD	Radio Device
RED	Radio Equipment Directive
RF	Radio Frequency
RIT	Radio Interface Technology
RSSI	Received Signal Strength Indicator
SAP	Service Access Point
SUT	System Under Testing
TC	Technical Committee
TS	Technical Specification
TSS	Test Suite Structure
TP	Test Purpose
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communications

1. INTRODUCTION

For any product implementing standardised radio technology within the EU, it must satisfy legal requirements before it is allowed to be used or placed on the market [1]. It is equally important that radio devices are made to be able to reliably communicate with a receiving counterpart implementing the same technology. This is achieved by following a widely agreed way of communicating, i.e., standardised protocols. Verifying these requirements involves testing which may be done in a standardised manner called conformance testing.

A widely used and mature radio technology such as the 3GPP LTE could be considered as an example of a developed radio technology, it includes a set of standardised test specifications [2] and test suites used to ensure conformance with its related standards. It also includes standardised methods for proving compliance with regulatory requirements within the European Union [3].

For a new technology such as DECT-2020 NR the standardisation work is under development, and documents such as conformance testing specifications do not yet exist, but development of products implementing the standard may very well be underway. For getting products as fast as possible to the market it might be wise to not wait for the conformance specifications to be released to do protocol testing but rather to initially attempt to comply with the essential regulatory requirements.

Protocol implementations may always be improved afterwards with updates to better conform with the relevant standards, and even go beyond them. After the release of standardised conformance specifications, testing for the protocol functionalities may be done in a commonly agreed way which reduces the time that manufacturers would otherwise need to use for defining the scope of testing for their products and how those functionalities should be tested.

In this thesis, harmonised standard testing against the regulatory requirements is conducted against an implementation of DECT-2020 NR, focusing on the MAC layer functionalities. The thesis shows a description of the test process with an example of the expected results when a radio device is assumed to conform with the regulatory requirements.

Another topic of the thesis is to propose a set of initial test purposes focused on the DECT-2020 NR MAC layer specification. The test purposes are defined for future use when standardising protocol conformance test specifications. The tests in this thesis will be designed for features that can be observed in any communication between two radio devices using the DECT-2020 NR technology.

A longer-term goal will be to develop a wide range of test purposes also for the CVG and DLC protocol layers. As no test specifications, test suites, or test equipment yet exist for the DECT-2020 NR standard, conformance testing against an early implementation needs to be done in an improvised way, which is covered with examples in this work.

Structure of the thesis

The introduction to the thesis is the first chapter. The introduction describes the content, scope, and the structure of this thesis. The second chapter introduces the reader to the European legislative environment which may be considered as the main motivation behind the testing of a radio protocol implementation. The main focus is on the Radio Equipment Directive (RED) and harmonised standards, and how they are linked to each other.

The third chapter describes the meaning of conformance testing from the protocol testing point of view. Since conformance testing is done in a standardised manner, the conformance specification consists of a set of documents having different purposes. The chapter describes the purpose of these documents and how they are used in actual conformance testing. For example, it describes the elements contained in test cases and explains how the test cases are chosen for a specific implementation.

The fourth chapter introduces the DECT-2020 NR radio interface technology for which the test cases are being defined, and for which the testing against the regulations is conducted. The chapter briefly describes the background for DECT-2020 NR, its operating principles, and the essential control functions that the MAC layer performs.

The fifth chapter includes a physical test setup implementing harmonised standard testing for DECT-2020 NR. The testing is essential for manufacturers to get their products implementing the technology to the European market. The chapter shows how these tests can be implemented against a real implementation with typical RF laboratory equipment. The chapter aims to show the expected results which would indicate regulatory compliance for an implementation.

The sixth i.e., the test definitions chapter introduces a set of basic test cases which are derived from the DECT-2020 NR core specification and describes the motivation behind implementing them by describing their purpose. The chapter is limited to include tests for only the MAC layer functionalities. The seventh chapter briefly shows possible methods for testing an early implementation against the test purposes defined in a testing specification. The conclusion as the eighth chapter wraps up the thesis by summarising the content and bringing up noteworthy points and briefly mentioning future considerations.

2. EUROPEAN REGULATORY ENVIRONMENT

This chapter discusses the regulatory aspects which affect the use of radio equipment and the spectrum.

2.1 Radio spectrum management

In the EU, the use of the radio spectrum is managed by authorities on regional and national levels by employing laws for radio transmissions to prevent interference between users. The use of the radio spectrum is further coordinated on an international level by the International Telecommunications Union (ITU). [4]

The regulated radio spectrum spans from 9 kHz to 3000 GHz and is widely used in modern technology. Although the radio spectrum is very wide, only a fraction of it is used due to economic and technical limitations. As an example, in Finland, approximately 99% of all radio equipment (licensed and unlicensed) operate on frequencies below 10 GHz. [5]

On the EU level, the European commission, European Telecommunications Standardisation Institute (ETSI) and the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) cooperate on the regulatory environment for radio equipment and spectrum [6]. The ECC develops the regulations and does the technical work to harmonise the efficient use of the radio spectrum within the EU. This includes making the decisions regarding the allocation of frequencies for radio communication services and the requirements for radio equipment to use the spectrum [7].

The essential requirements for constructing radio equipment to both effectively use and support the efficient use of the radio spectrum to avoid harmful interference are harmonised via the Radio Equipment Directive (RED) [6].

Member states in the EU, i.e., the EU countries manage the use of the radio spectrum according to EU legislation and international agreements, which harmonises the spectrum use across the EU [4].

2.2 Radio Equipment Directive

A directive is a type of legislative act that sets a goal for the EU member states to achieve [8]. These goals are described in a directive as requirements. As the requirements are often described at a high level, each member state of the EU must come up with methods on how to reach these goals [8]. Individual countries may change or create national laws to steer their behaviour towards satisfying the requirements. For this thesis, the directive of particular interest is the Radio Equipment Directive (RED) (Directive 2014/53/EU).

The Radio Equipment Directive (RED) [1] establishes a regulatory framework for placing radio equipment on the market. It sets essential requirements for safety, electromagnetic compatibility, and radio spectrum usage. It also includes topics such as protection of privacy, data, fraud, interoperability, emergency services and the compliance of the combination of radio equipment and software.

Scope of the directive

The directive applies to radio equipment that is intended primarily for consumer and company use and does not apply to activities concerning state security and defence, as well as criminal law [1]. Additional equipment not covered by the RED is described in annex 1 of the RED [1]. The radio equipment directive defines the term: “radio equipment” as an electronic product which intentionally transmits or receives radio waves for the purpose of communication or radiodetermination [1].

Directive requirements

Article 3 of the RED lists the essential requirements in 3 categories to reach compliance with the directive. The requirements give directions on how all radio equipment shall be constructed with additional requirements concerning some device categories. It is up to the manufacturer of the radio devices to decide how to comply with these requirements. Because the requirements are described at such a high level, supporting harmonised standards are produced to harmonise the methodology to assess compliance with the requirements.

The first requirement of the RED (Article 3.1) states that the radio devices must be safe for the health of persons and domestic animals. The second requirement (Article 3.2) states that the radio equipment must be constructed in a way that the radio spectrum is used efficiently and avoids interfering other devices sharing the spectrum. The third requirement (Article 3.3) applies to radio equipment within certain categories, by introducing needs to support certain features for various cases and capability for interworking with accessories and networks to a certain extent [1].

For this thesis, requirement 2 of Article 3 of the RED is the main interest [1]. It is identified to be the relevant requirement to be tested and is described later in this thesis.

References to other directives

Because radio devices are usually a mix of hardware, and software and produce electromagnetic waves, they fall into the scope of several directives. The requirements of the RED refer to the requirements of the related directives where appropriate.

The requirements in the directive refer to the electromagnetic compatibility directive (ECMD), in which radio devices are required to keep their electromagnetic interference at such levels that it allows other devices to function normally. ECMD also requires the devices to have a certain level of immunity to electromagnetic disturbance to operate in their typical environment (Directive 2014/30/EU). [9]

Electromagnetic disturbance is defined as being electromagnetic phenomenon which degrades the performance of a radio device. Such as noise, or an unwanted signal. [1] [9]

The health safety requirements of the RED refer to the safety requirements specified in the Low Voltage Directive (LVD) (Directive 2014/35/EU) without voltage limits, where the purpose is to fulfil requirements for the protection of health and safety of persons, domestic animals, and property.

CE marking

The CE marking “Conformité Européenne” (Engl. European Conformity) is a requirement for products to enter the European Economic Area (EEA) (EU and EFTA countries). The CE marking enables the free movement of products within the European market and can be achieved by complying with the relevant European legislation [10].

Manufacturers must demonstrate compliance with the requirements and can then affix the CE marking to a product. By affixing the CE marking on a product, the manufacturer declares and is responsible that the product conforms with all the related legislation [10]. The CE marking does not indicate that the product is approved by the EU since it is only a declaration by the manufacturer. A set of detailed instructions exists on how the CE marking must be affixed to a product [11].

Figure 2.1. *CE marking that is affixed to a product complying with the related legislation [11].*

Surveillance and non-conformity

The EU member states are required to take measures to ensure that equipment placed on the market and put into service comply with the requirements of the directive. To do this, surveillance authorities may randomly test products on the market as a part of a systematic program or after being informed via complaints. [6]

National surveillance authorities are allowed under the Radio Equipment Directive to gain access to information on the radio equipment. Technical documentation and declaration of conformity need to be made available for inspection by the manufacturer. [6]

In cases of non-compliance with the directive, manufacturers are required to either implement adequate corrective actions to bring the radio equipment into compliance or withdraw or recall the product from the market within time related to the risk that the product may cause [1]. Additionally, proportionate penalties may be given for infringements to the directive.

Notified bodies

A notified body is an organization which a member state of the EU has recognised to be capable of carrying out conformity assessment according to a specific directive such as the RED and notified this to the Commission and other member states. Notified bodies may perform conformity assessment and issue certificates for harmonized products in the area for which they are notified. [12]

The EU also concludes Mutual Recognition Agreements (MRA) with countries outside the EEA to designate conformity assessment bodies (CAB) in those countries. The MRA are bilateral, such that the designated CABs of both parties may show compliance with the requirements of the other party. The purpose of the agreements is to promote trade between regions and facilitate market access. [12]

2.3 Harmonised standards

Harmonised standards, also known as EN standards, are European standards developed by a recognised European standardisation organisation, either CEN, CENELEC, or ETSI, following a standardisation request (mandate) from the European Commission [13] [10]. The creation process is initiated by identifying the need to support a relevant directive, such as the radio equipment directive (RED).

The purpose of a harmonised standard is to have methods to assess conformity with the requirements of related EU legislation and to be referenced by them [13] [14] [10]. As the requirements of a directive are written in a way that is very non-specific, harmonised standards aid by defining detailed methods on how to meet the requirements of the directive [14].

A standard is called ‘harmonised’ after its references are published in the Official Journal of the European Union (OJEU). After the publication, conformity with the standard can be used as a presumption of conformity with the related directive requirements [10]. After the publication of the standard, the member states (EU countries) must adopt the standard and withdraw any conflicting standards.

The methods for proving conformity in a harmonised standard may for instance be test methods, with a detailed description of the test procedure to be performed. The test methods for harmonised standards are specific to technology. They refer to functionalities and requirements defined in the core specification of the technology in order to define clear goals which allow an implementation to satisfy legal requirements. Although referring to the core specifications, the harmonised standard conformance requirements are not directly derived from the conformance requirements of the related standard.

It is not mandatory to use the methodology specified in a harmonised standard to prove conformity if the conformity with the legal requirements can be proved by alternative means [13]. For instance, if a harmonised standard has not been published, a notified body may still perform conformity assessment for products in the area it is notified.

By complying with the relevant harmonised standards, and thus with the related EU directives, the CE marking can be affixed to the product and placed on the market. It can therefore be considered that testing against the requirements of the harmonised standards is one of the main motivations behind testing for companies within telecommunication industries.

3. CONFORMANCE TESTING

This chapter describes conformance testing elements of a protocol implementation, focusing on the different contents of a test specification and how test cases are derived from the core specifications of a standardised technology.

3.1 Target of conformance testing

Testing in general is the act of evaluating the functionality of something to ensure desired outcomes. For manufacturers, it is useful to identify errors, faults, or missing requirements in their products. Testing enhances the overall quality and reduces the likelihood of issues occurring in the real use of a product.

Conformance testing is testing that tests an implementation to what extent it meets the requirements of a standardised technology [15]. The aim of conformance testing is the interoperability between different implementations of a standard [16]. Products implementing standardised technology, such as radio transceivers implementing communication protocols, need to be able to communicate with devices of other manufacturers implementing the corresponding standardised protocols.

Conformance testing provides a certain level of confidence that a standard is followed properly, such that the implementation has all the required capabilities [17]. As with any testing, conformance testing should not be aimed to be too exhaustive, since it would grow the number of test cases very high [17]. It is thus recommended that the features are only tested for events that may occur during real use.

In conformance testing, the target of testing is usually called either system-, implementation- or equipment, etc. under testing (SUT, IUT, EUT), which depends on the test scope. A SUT is a broader scale term referring to the entire system, which may include both the IUT and its surrounding system, such as other protocol layers. The term IUT can be used when the scope of testing is more focused on a part of a system, such as a module or a single functionality, such as a specific protocol layer implementation. EUT may be used when the target of testing is a combination of hardware and software, i.e., an equipment or a complete product.

Another target of conformance testing is to develop a common test methodology by standardising stable and widely applicable methods of testing [17]. When the test methods are standardised, anyone implementing the technology can use the shared test specifications to assess conformity with similar methodology.

Conformance testing can be considered as ‘black box’ testing, meaning that the tester does not have to know what is happening internally within the implementation, and the only way to test the implementation is to observe the behaviour that can be seen externally. Additionally, to avoid biased test results, the target of testing should not be aware that it is being tested.

Due to the ‘black box’ nature of conformance testing, it can be carried out by several parties. The initial testing should be done thoroughly by the manufacturer itself to confirm that it meets the requirements of the standards. After the manufacturer is satisfied with the initial testing, the implementation may be given to an independent testing laboratory, where it can be tested to obtain unbiased test results and be issued a voluntary certification for conforming with the related standards. Voluntary certifications do not have any regulatory significance [12], but may help to increase the market appeal of a product.

3.2 Conformance requirements

Conformance testing is testing against the conformance requirements of the core specification or a profile of standard. A conformance requirement is a detailed description in a protocol specification which states how a feature in an implementation is required to function. A feature in a core specification typically consists of multiple conformance requirements that need to be met for an implementation to conform.

A well-made core specification uses the verbs **shall**, **should**, and **may** and their negative counterparts correctly to implicate whether a requirement for a feature is mandatory or optional [14]. The verbs “shall” and “shall not” express that a requirement is mandatory, and “should” and “should not” are used when a requirement is recommended or expected to be implemented unless there is a strong reason for not doing so. “May” or “need not” is used for permissions, meaning optionality. [14]

Since every feature of the core specification is not required to be implemented in every implementation, also the features are given requirements that can be stated as mandatory, optional, or conditional. It is up to the protocol specifier to state which features are mandatory, i.e., required for the core functionality. This reduces the need for unnecessary testing and implementation of unneeded features.

3.2.1 Conformance requirement types

Conformance requirements in core specifications are either dynamic or static. **Dynamic requirements** specify exactly how the implementation is allowed to function and what observable behaviour is allowed [17]. Dynamic requirements are essential for communication, for example, responding to a request message with a logical response message, or behaving in a certain way after acquiring a value in a specific range from a measurement.

Static requirements describe requirements that do not change over time or are not affected by previous events [14]. Static requirements specify exactly what content a message should contain and are more focused towards specific values and structures [17].

A single test case can test both the static and dynamic requirements. As an example, a test can test the behaviour of a procedure, where the receiver should send a response message after receiving a request, which is a dynamic requirement, and the response message should be transmitted using a specific header and include a defined set of information elements (IE), among other optional content or restrictions as static requirements [18]. It could be considered that the dynamic requirements cannot be correctly met if the static requirements are not initially met.

3.2.2 Conformance requirements for profiles

A protocol profile defines a set of options from the core specification that are relevant to provide a required functionality for a specific use case such as mMTC and URLLC for IoT [17]. Protocol profiles limit and refine the requirements of a core specification. The conformance requirements that are retained in a profile are references to the core specification, meaning that the requirement will stay as it is. A profile can also introduce additional, profile-only conformance requirements that refine the core requirements and are more specific and limited in scope than in the core specification [16].

By having implementations based on a profile intended for a specific functionality or a use case, it is more likely for them to interoperate, as there is only a limited set of capabilities and requirements that a manufacturer needs to focus on.

Conformance testing for profiles is done according to the tests of the core specification where applicable. Depending on the profile, different testing parameters might be used, such as varying message contents or values. Profile-only test cases are applied only if refined, or profile-only conformance requirements are present.

3.3 Conformance test types

ISO/IEC 9646-1 [16] distinguishes 4 types of conformance testing, each proving conformity to a certain extent with relevant specifications.

- Basic interconnection tests
- Capability tests
- Behaviour tests
- Conformance resolution tests

3.3.1 Basic interconnection tests

Basic interconnection tests offer limited testing of an IUT concerning the main features in the base standard or profile specification. The goal of basic interconnection tests is to confirm that there is adequate conformance for interconnectivity to be possible, without undertaking a comprehensive testing process. [16]

The basic interconnectivity tests are a good set of tests to start with before advancing with further, more comprehensive testing. They provide the tests for mandatory features to enable communication between implementations. The more detailed testing relies on the basic interconnection tests passing. As an example, an implementation must be able to send and receive messages correctly to be able to further behave according to the message contents. The basic interconnectivity tests alone are not sufficient to assume conformity with the standards.

3.3.2 Capability tests

Capability tests test whether the capabilities stated in the Protocol Implementation Conformance Statement (PICS) can be observed [16]. These can be verified by testing the static conformance requirements of the capabilities. As an example, a capability may include the use of a specific message type defined in its specifications i.e., having the message structure as the static requirement. The capability tests are not detailed and do not provide information in the case of non-conformity.

3.3.3 Behaviour tests

Behaviour tests are detailed tests that form most of a test suite. They test the dynamic conformance requirements of a specification as comprehensively as possible. Behaviour tests verify if the IUT responses are valid in scenarios where the other participant, i.e., the tester has either valid (BV) or invalid behaviour (BI) [16]. In protocol testing, most of the behaviour tests should test the valid behaviour of the protocol. The purpose of invalid behaviour testing is to try to trick the IUT into doing something unexpected, rather than handling the event as an error or completely ignoring it.

As an example, a tester intentionally transmitting an undecodable packet or the tester not sending a response when requested could be considered as invalid behaviour from the tester's point of view but from the IUT point of view these are typical scenarios which are defined in the specification and can be considered as valid behaviour tests.

Actual invalid behaviour testing could be that the messages sent by a tester do not conform with the static requirements, i.e., values are out of an allowed range etc. The behaviour how the IUT should behave in these kinds of scenarios is not defined in the specifications and should be treated as error cases or ignored. As it is possible to come up with a very high number of invalid behaviour tests by having different invalid parameterisations, using them extensively as a part of a test suite is not recommended.

3.3.4 Conformance resolution tests

Conformance resolution tests are tests that are not standardised due to them being implementation specific. This means that these kinds of tests require the use of internal observation of the IUT, or artificial generation of events to observe if the IUT behaves according to a conformance requirement [16]. As an example, using debugging logs to prove conformity, would suggest that the test cannot be considered as ‘black box testing’. These types of tests can be used to test conformance requirements that are deemed untestable by a standardised test suite.

3.4 PICS

As discussed in an earlier paragraph, an implementation of a standardised technology is not required to implement all the capabilities defined in the core specifications. Instead, the capabilities that are required to be implemented are usually a part of the core functionality of the technology, and further supplemented by requirements defined in a profile specification aimed for a specific use case.

An ICS is a statement of a manufacturer, which capabilities have been implemented. An implementation conformance statement (ICS) concerning a protocol implementation is called a PICS (Protocol ICS). The PICS is a result of filling in a standardised PICS proforma.

3.4.1 PICS proforma

The protocol implementation conformance statement (PICS) proforma is a document in the form of a questionnaire, which lists all the features of a protocol specification. The manufacturer of the implementation needs to fill in the proforma to state which of these features and options have been implemented. A completed PICS proforma becomes a PICS. [19]

In standardised ETSI test suites [20], the PICS proforma entries are commonly expressed as shown in Table 3.1 below. This type of feature listing allows for a detailed declaration of what is implemented. Additional tables concentrating on a single entry on another table will make the PICS even more detailed.

Table 3.1. *An example table for declaring supported features. The title of this table in a PICS proforma document should be e.g., Table x.x: MAC Messages.*

Prerequisite: X.Y/Z (indicating a table entry about supporting MAC Messages)				
Item	**MAC Message**	**Reference**	**Status**	**Support**
1	Network Beacon message	[18] clause 6.4.2.2	m	
2	Cluster Beacon message	[18] clause 6.4.2.3	m	
3	Association Request message	[18] clause 6.4.2.4	m	
…	…	…	…	

The prerequisite field indicates that the table shall only be filled if the corresponding feature is declared to be supported, as an example for DECT-2020 NR, if the RD is only capable of random-access transmission, it should not need to fill in the features required for scheduled-access transmission. The “support” field is reserved for the use of filling out the questionnaire.

Each of the entries of the PICS proforma includes status values. They describe the requirement level and dependencies of capabilities. The status values and their meaning are shown in Table 3.2 below.

Table 3.2. *Possible status values for ICS entries [19].*

Status	**Description**
Mandatory: m	The capability shall be supported.
Optional: o	The capability may or may not be supported. It is an implementation choice.
Not applicable: n/a	It is impossible to use the capability.
Prohibited: x	It is not allowed to use the capability. Common for profiles.
Conditional: c<integer>	The requirement (“m”, “o”, “n/a”, “x”) depends on whether other optional or conditional items are implemented, identified with <integer>.
Qualified optional: o.<integer>	For selectable options from a set. The group of options indicated with <integer>.
Irrelevant: i	Capability outside of the scope of the given specification.

PICS proforma for profiles

A PICS proforma for a protocol profile is acquired by modifying the requirement status values of the base ICS proforma according to a list of requirements defined in a profile specification. A profile should only restrict the number of options, by noting some requirements which have been optional “o”, to be mandatory “m” or conditional “c” in the profile, but not the other way around. Some requirements which may be out of the scope of the profile, or which cannot be implemented should be stated as irrelevant “i” in the profile PICS proforma. [19]

3.4.2 Applicability of test cases

The completed PICS summarises to which degree a manufacturer declares the implementation to conform with the standard, and which optional capabilities are supported.

The entries in the PICS are used to provide answers to whether related conditional test cases are applicable to a specific implementation. The tests may either be linked directly to the PICS entries, i.e., the elements in the tables, or their relations can be stated in a separate document.

Since conformance testing is not mandatory from the point of view of placing products on the market, although very recommended, a notable difference is that requirements can be mandatory, but their related test cases can at most be “recommended”.

3.5 TSS&TP

TSS&TP (Test Suite Structure & Test Purpose) is a document, part of a conformance testing specification that includes the structure of the test suite and the test purposes i.e., the abstract test definitions. The test specification document may not be named exactly as TSS&TP if the conformance specification is divided into multiple documents. As an example, the document including test purposes for 3GPP 5G, and LTE user equipment is simply called a conformance specification, with a focus on protocol testing. [21]

TSS (Test Suite Structure) defines the scope of testing the test specification applies to the reference specification. It defines which tests are performed to which part of the reference specification. A TSS may be as simple as categorizing the test purposes in a tree-like structure to the test specification document.

A set of rules applies to the TSS [17].

- A top-down approach should be used when deriving the TSS from the core specification.
- When creating the TSS, it should be structured as a tree, where the test purposes are grouped in the leaves. According to ISO/IEC 9646-2 [22], a single test purpose is allowed to belong to multiple different test groups, but a reference is used instead of replication of the TP.

The TSS tree structure is highly dependent on the reference specification in question. An example of possible levels for a DECT-2020 NR TSS is given below.

1. The name of the core specification on top (root) e.g. DECT-2020 NR
2. Test groups for different protocol layers e.g. PHY, MAC, DLC, CVG.
3. Test groups for major functions and roles e.g. functions for both FT-mode and PT-mode for the MAC layer.
4. Pre-defined groups of tests according to their nature.
    a. Basic interconnection tests.
    b. Capability tests.
    c. Valid behaviour tests.

    d. Invalid behaviour tests.
    e. Inopportune behaviour test
5. Pre-defined groups of tests according to their functional aspect
    a. State event transitions.
    b. Parameter variations.
    c. Parameter combinations.
    d. Timers.

For the actual implementation of the TSS, the levels are customised to better fit the protocol structure.

3.6 Test purposes

In the context of ETSI, “Test Purposes” (TPs) are part of a telecommunication standard and are produced by the group drafting the test specification [17].

A single test within conformance testing is implemented according to a test purpose. Test purposes define unambiguously the objectives of each test and the logical way they are supposed to be used. Test purposes are derived from the conformance requirements of the core specification. They focus on a single conformance requirement or a set of related requirements [17]. A test purpose is an abstract description of the performed test, meaning it does not specify how the test itself should be performed in practice.

A single conformance requirement may be linked to multiple test purposes, such as testing for valid, invalid, and inopportune behaviour. To optimise testing, the test purposes belonging to a single feature should be grouped in the test specification and executed within a single test procedure, as is done in 3GPP 5G protocol testing [21].

3.6.1 Test-purpose structure

The structure of a test purpose is defined in [22] test purpose style guide.

Identifier

A TP should have an identifier that can be used to link the purpose elsewhere in the testing specification, such as to the test suite structure or the PICS. As an example, the clause in which the test purpose is defined in the TSS&TP can be used as a reference elsewhere and thus replaces the need for a unique identifier.

Reference to requirements

A test purpose (TP) must have a reference to a clause in the reference standard, where the requirement is defined.

Initial conditions

A TP shall always contain the initial state of the IUT from which the test should be initiated [22]. The initial state needs to be unambiguously identifiable by external observation of parameters. This can be achieved by defining the initial state in a way that the state change to the initial state is possible to be observed by a semantic action, i.e., the IUT transmitting or receiving a specific message.

However, a TP does not need to define how to reach the initial state. Since many test purposes may have the same conditions for the initial state, the procedures for reaching the state may be included in the conformance specification as a common test procedure. The method how the initial state is reached in a test is also called the preamble of the test.

An initial-state requirement of a test purpose may very well be the result of another test purpose completing its test body. These kinds of test purposes enable the possibility of having multiple test purposes chained together to a single test sequence.

Checks

Test purposes must specify what checks should be performed. Specifying a check for a test purpose should be unambiguous. It should be explicitly stated which valid events are allowed to be observed. If the check is defined by only stating that: “check if the response is valid”, it will be difficult for the tester to figure out from the reference specification which responses are valid.

Checks can be included in a test procedure chart along with the TP number and the related verdict. A test procedure chart gives a more detailed overview of the whole test procedure and may be included in a testing specification after test purposes as is done in [21]. Having a procedure chart included in a test specification is helpful when implementing test cases in practice.

Verdict criteria

The verdict criteria describe the observable events which are used for assessing the test result. The verdict criteria are included in the checks and describe whether the observable event shall happen or not.

Constraints

The use of constraints is considered differently for parameter variation test cases than for other tests. For test purposes not focusing on specific values, the use of constraints should be avoided if no benefit is acquired. For parameter variation tests, the constraints should indicate which parameters or elements it tests [17].

3.6.2 TPLan: A notation for expressing Test Purposes

A standardised method to write the test purposes for test specifications is a notation called TPLan [23]. TPLan benefits from having a clear structure where TP pre-conditions, test body and verdict criteria are clearly identified. Using a structured notation and having a limited set of keywords for writing all test purposes and writing them in a consistent way, reduces the chance of misinterpretation when designing abstract test cases.

The main content of a test purpose i.e., the body structure and syntax are defined in section 11 in ETSI ES 202 553 [23]. TPLan includes keywords which can be used to specify the test stimulus conditions and response contents unambiguously. These keywords used in the test body are listed in the Table 3.3. For convenience, the notation is allowed to be extended by the test definer to include useful keywords for the technology to be tested, such as message names and parameters.

The test purposes written in TPLan are from the IUT point of view, meaning that the keywords such as ‘sends’ and ‘receives’ refer to the IUT sending or receiving.

The main behaviour for all test purposes is written inside curly braces after the keyword ‘**ensure that**’. The TP behaviour consists of stimuli and response, defined with the keywords ‘**when**’ and ‘**then**’, both enclosing the stimuli and response as text inside curly braces. The TP should include a pre-condition which is expressed with the keyword ‘**with**’. The precondition is written outside and before the TP behaviour body. As mentioned in the previous paragraph, the precondition does not include the required steps to reach the initial state.

The behaviour is written as conditions to be met. Expected behaviour having multiple or optional conditions should be separated using ‘and’, and ‘or’, and the desired order of fulfilling conditions using temporal ordering words such as ‘before’ and ‘after’. [23]

An example of the syntax of the test purpose is shown below, specifying the content of a message with keywords ‘containing’ and ‘indicating’. The test purposes are written as following in the test specification.

(1)

```
with {IUT in ‘initial state’ and ‘ready’}
ensure that {
      when {IUT receives ‘a stimulus’ from TESTER containing ‘field x’ indi-
cating ‘value’}
      then {IUT sends ‘a response’ to TESTER containing ‘field y’ indicating
‘value’}
            }
```

The when-then structure is allowed to be repeated multiple times in one TP to define a sequence [23].

The content of the initial condition, stimuli, and response (within the brackets of with, when, and then) may also be written in more open words to make the syntax more fitting to the context. As an example, if an IUT is required to retransmit after a negative acknowledgement message, instead of “IUT sends”, “IUT retransmits” could be written.

Table 3.3. *TPLan defined keywords used in the test body [23].*

TP body keywords	
ensure	Ensure
that	That
with	With
when	When
then	Then
Test entity keywords	
IUT	iut
TESTER	tester
TPLan glue words	
a	A
an	An
as	As
in	In
is	Is
no	No
of	Of
the	The
Logical words	
and	And
not	Not
or	Or
Stimulus and Response words	
receives	Receives
sends	Sends
Data-related words	
containing	Containing
indicating	Indicating
Direction-related words	
from	From
to	To
Time- and order-related words	
after	After
before	Before
unordered	Unordered
within	Within

4. DECT-2020 NR

4.1 General

DECT-2020 NR (Digital Enhanced Cordless Telecommunications 2020 New Radio) is a wireless CP-OFDM-based radio interface technology designed for non-cellular local area wireless networks, produced by ETSI technical committee DECT. The radio technology standard is referred to as “DECT-2020 NR” by ETSI or simply “NR+” by the DECT Forum as a marketing name [24]. In this thesis, the naming convention used in the ETSI specifications will be used.

DECT-2020 NR does not replace the legacy DECT but instead shares the regulations and co-exists with it on the licence-exempt 1.9 GHz band. The DECT-2020 NR is based on the legacy DECT but differs significantly in technical and conceptual aspects [25]. The legacy DECT (Digital Enhanced Cordless Telecommunications) is a radio technology originally developed by ETSI as a European standard in the 1990s which has since supported voice and data services on the DECT spectrum [25].

The DECT-2020 NR radio interface technology is targeted for URLLC (Ultra Reliable Low Latency Communications) and mMTC (Massive Machine Type Communications) applications such as smart cities and industrial IoT (Internet of Things), as well as professional audio applications [25]. A DECT-2020 NR network may be set up anywhere at any time without the need for external cellular infrastructure. This is achieved due to it being non-cellular. The non-cellularity may prove especially beneficial in remote areas where the cellular coverage can be weak.

The technology is officially recognised by ITU-R as an IMT-2020 technology satisfying the requirements for both the URRLC and mMTC use cases, making it a part of the 5G standards, and the world's first globally recognised non-cellular 5G technology [25].

The IMT-2020 requirements for mMTC use case state that the technology shall support device densities of 1 million devices per square kilometre, while still reaching the desired QoS requirements [26]. DECT-2020 NR can manage such massive deployments due to utilising mesh topology, using multiple channels dynamically and having cognitive radio functions to avoid the need for precise frequency planning, while also having state-of-the-art radio capabilities [27]. The mesh topology allows the networks to not have a single point of failure, meaning that if a routing link fails it can heal the network by autonomously forming a new connection [25].

While DECT-2020 NR is mainly associated with operating in mesh network configuration to provide widely scalable networks, it is also capable of point-to-point, or point-to-multipoint links to provide conventional wireless links between devices as well as operate with a cellular configuration where one device acts as a base station while other devices do not route data [18].

The DECT-2020 NR is defined in the multipart ETSI TS 103 636 standard series. For this thesis, part 4, the MAC layer specification [18] is of particular interest.

4.1.1 Radio Device FT and PT modes

All communication between radio devices (RDs) in DECT-2020 NR happens between RDs operating in FT (Fixed Termination point) and PT mode (Portable termination point). All RDs, independent of their operating modes, can transmit and receive messages. It should be noted that the operational modes are relevant only at the MAC layer.

Radio devices in FT mode sense the radio environment and provide radio resources and other information for the devices operating in PT mode to enable communication with them. The RDs in FT mode announce this information in periodic beacon messages.

Devices in PT mode operate on the radio resources and according to the information provided by the RD in FT mode. The RDs in PT mode can join a network by initiating an association procedure with an RD in FT mode.

For communication between two devices to work in both directions, a device needs to operate both in FT and PT mode in turns. This also enables the radio devices to route data from an RD to an RD that otherwise would not be reachable with a single radio link. A device capable of only operating in PT mode has to indicate radio resources for the RD in FT mode where it can receive data in downlink direction. This can be indicated for example during the association procedure.

A radio device that only operates in FT mode is called a sink, since it does not forward any data between RDs and usually has a connection to the outside world, e.g., internet or backend connectivity. A radio device that only operates in PT mode does not route any data but only receives or sends data.

4.1.2 Mesh operation in DECT-2020 NR

A mesh network is a local area network topology. In a mesh network, all devices are connected, either directly or via other devices. A device in a mesh network is called a node. If there is not a direct connection between nodes, any messages sent need to be routed via other nodes to reach the destination node. The nodes relaying messages are called router nodes, and the nodes that only send or receive messages intended for them are called leaf nodes. The root node, which has backend or internet connectivity is called a sink.

A DECT-2020 NR mesh network is a partial mesh, forming a clustered tree topology [28]. A set of RDs where the RD in FT mode coordinates the RDs in PT mode forms a single cluster. All RDs in PT mode that also operate in FT mode, can form additional clusters of their own to widely extend the network as shown in Figure 4.1. Each of the clusters operates on its own channel and is coordinated by the cluster head (device in FT mode) sending cluster beacons on the operating channel.

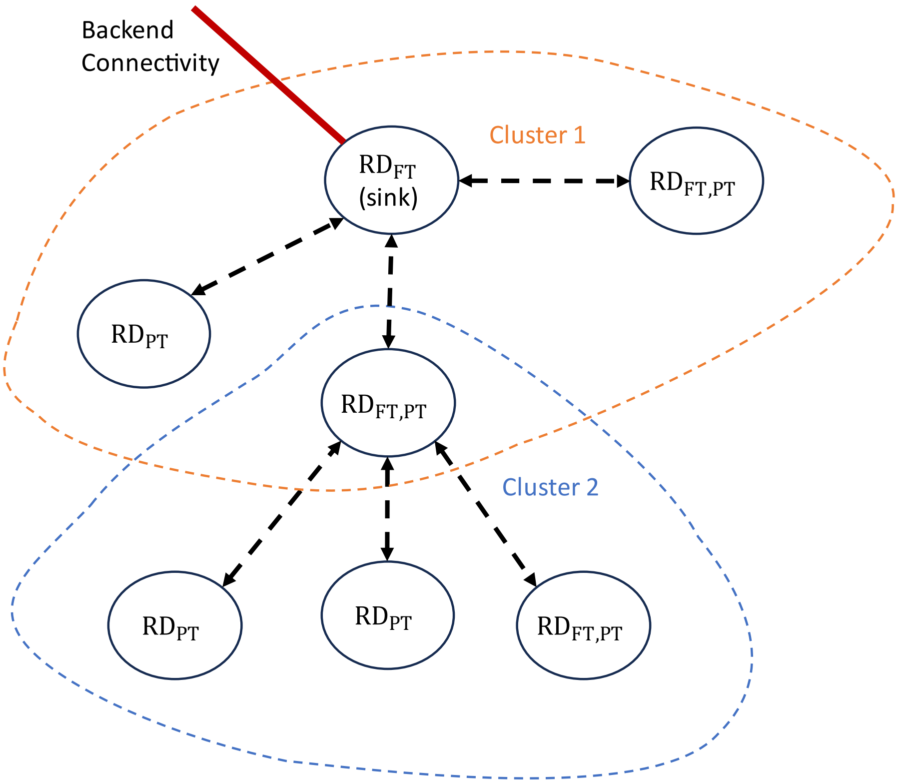


Figure 4.1. *Clustered tree topology formed by DECT-2020 NR radio devices.*

The network is formed autonomously by devices in PT mode connecting to other RDs operating in FT mode that have the best route to a sink. The goodness of a route is determined by its cost value, which is calculated from the number of hops, their quality and load. The route information is signalled by the RD in FT mode in the periodic beacon messages [18]. This allows the RDs to always have the best possible routes to the sink.

Over time, the quality of the radio link and the route cost to the sink may vary due to mobility, changes in the network, variations in load or other interference, therefore the RDs can begin to search for better options to reach the sink, keeping the network as efficient as possible.

Overall, the possibility for the DECT-2020 NR mesh network to scale to high densities comes from that each RD is capable of routing data, and every radio link is locally managed by the RDs in FT mode, while also being able to use multiple frequency channels for minimising interference.

4.2 MAC control entity functions

The DECT-2020 NR MAC layer specification defines 6 functions for the MAC control entity. These functions work together to provide data transfer and resource allocation services to upper layers. The physical layer provides the MAC layer with measurements, and data transfer services in the form of physical layer packets.

These control functions are only briefly mentioned in the MAC layer specification [18] but could be considered to provide important MAC functionality according to the tasks described.

4.2.1 Local Radio Control (LRC)

The local radio control (LRC) function handles the coordination of local radio resources when the RD is operating in FT mode [18]. Resource control includes the task of announcing random-access resources and dedicating scheduled-access resources where it can receive data or use them for its own transmissions. For defining which channel and sub-slots it can announce or transmit on, it uses the measurements provided by the physical layer to define the status of each sub-slot of a radio frame on each channel either occupied or usable. The statuses of the sub-slot resources are regularly updated using the last-minute scan (LMS) protocol before announcing them for use.

4.2.2 Paging Transmission Control (PTC)

The paging transmission control (PTC) controls the transmission of paging messages when the RD is operating in FT mode [18].

The paging transmission may be used when the RD in FT mode wants one or multiple RDs associated to it become active towards it. Transmitting a paging message in DECT-2020 NR can be used to either indicate that the connection configuration requires modification, or to check whether an RD that has not been active for a while is still reachable and will reply with a keepalive message. The paging messages are always multiplexed with cluster beacon messages.

4.2.3 Broadcast Control (BCC)

The broadcasting control (BCC) function controls the beaconing, broadcast, and multicast transmissions, i.e., the transmissions not targeted towards a single RD [18].

Beacons transmit information available for all RDs on how they may connect to the RD in FT mode transmitting them. They allow the RDs in PT mode to make decisions on which FT device they want to connect to. Not only do the beacons give information but they may be measured to associate information about the link quality to specific RDs and networks. Beaconing in DECT-2020 NR is an essential function to form efficient routes for mesh networking.

There are two types of beacon messages in DECT-2020 NR, cluster, and network beacons. Network beacons can be transmitted on a limited set of channels which allows RDs to quickly find the beacon and thus the operating channel of an RD. The cluster beacons are transmitted on the operating channel of the RD in FT mode. The cluster beacon provides the frame and slot timing such that the connecting RDs may synchronise to it. It also provides radio resources which the RDs in PT mode may use for communication.

The beacon messages are transmitted with any power level chosen by the RD, directly impacting the radius of the cluster. The RDs in PT mode may use the beacon transmissions to measure the link qualities between different beaconing RDs in FT mode to determine the link quality for each. The RDs may use this information to pick the most suitable RD for association and to adjust its own transmission power.

The beaconing messages are transmitted with a special beaconing header, which has fewer information bits, and thus provides better coding gain on reception, maximising the probability that the control information of the beacons is received successfully.

Generally, the broadcast and multicast transmissions are transmissions targeted for all or a group of RDs in the network. The transmissions can be either signalling or user-plane data. For signalling purposes, an RD in FT mode may use broadcasting to send multiple responses for random access transmissions with one message using the Broadcast Indication IE or to allocate scheduled resources for multiple RDs with one message with the Group Assignment IE [18].

4.2.4 Random Access Control (RAC)

Random access control handles the random-access transmissions [18]. Its purpose is to provide handling of the data transmissions occurring between devices which use random-access resources for communication.

Randomly accessing radio resources means not having the receiver in FT mode to allocate radio resources to a specific RD in PT mode, instead, all devices can attempt to use the resources as needed (time and frequency), which introduces contention. In DECT-2020 NR a contention-based multiple access scheme CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) is used, where a LBT (Listen Before Talk) protocol is used to control the transmissions.

4.2.5 Beacon Scanning Control (BSC)

The beacon scanning control function performs periodic scanning for network and cluster beacon messages, to detect networks and other nearby RDs to which an RD in PT mode may attempt to connect. For instance, periodic scanning of beacons is used to re-evaluate link conditions between RDs as a part of the mobility procedure.

4.2.6 Connection Configuration Control (CCC)

The connection configuration control function has several tasks. It controls the multiplexing, mapping data to transport channels, MCS (Modulation and Coding Scheme), HARQ (Hybrid Automatic Repeat request) configuration, MAC security and handovers with LRC [18].

The CCC function could be seen as the entity controlling the individual connections between two RDs. The connections are established during the association procedure where the identities and configurations are exchanged and agreed between the RDs FT and PT mode. In DECT-2020 NR, each RD may have multiple simultaneous connections with other RDs, one to an RD in FT mode and none or multiple towards RDs in PT mode.

The initial configuration for a connection may require modification due to feedback from the associated RD, or when the link quality deteriorates. The CCC adjusts the MCS for each transmission to reach the maximum throughput with a required QoS (Quality of service) [18]. The connections are maintained until explicitly closed by either of the RDs transmitting an association release message or deciding to release the association locally.

Multiplexing data involves the RD to multiplex MAC SDUs to a single MAC PDU creating specific control messages or data packets, which are then mapped to suitable transport channels.

The CCC controls the HARQ configuration, which includes the HARQ processes, their retransmissions and feedback signalling.

An RD in PT mode may briefly have two simultaneous connections to different FT RDs due to handover, i.e., the mobility procedure, where the association to the old RD is released only after the new connection is successfully established.

The CCC is also responsible for security procedures such as integrity protection and ciphering. The integrity protection generates message integrity code (MIC) based on the PDU content and affixes it to the end of the MAC PDU which can be used to check whether the data has reached its destination unchanged. Ciphering scrambles the MAC PDU in a way that it can only be deciphered by the intended recipient.

4.3 DECT-2020 NR Harmonised Standard

A supporting harmonised standard (ETSI EN 301 406-2) has been created for the DECT-2020 NR to harmonise the methodology for conforming with Article 3.2 of the radio equipment directive.

By comparing the harmonised standard requirements and the corresponding conformance requirements implementing the requirement functionalities, it can be noted that conforming with the requirements of the DECT-2020 NR specifications will also prove conformity with the regulatory requirements, but not the other way around. This is because the requirements of the harmonised standard are less tight than the specification counterparts.

At the time of writing this thesis, the harmonised standard for DECT-2020 NR has not yet been referenced in the OJEU. However, the harmonised standard has been published and thus the included methods may be used by a notified body to provide regulatory certification, allowing the placement of radio equipment implementing DECT-2020 NR to the market.

5. HARMONISED STANDARD TESTING

5.1 DECT-2020 NR Harmonised Standard for access to radio spectrum

The ETSI EN 301 406-2 is a harmonised standard for radio devices implementing DECT-2020 NR supporting access to the radio spectrum on the frequency band 1 [29] [30]. It includes voluntary testing methods for random and scheduled channel access. The harmonised standard has been created as a result of a standardisation request of the European Commission and prepared by the ETSI Technical Committee (TC) DECT to provide a means of conforming with Article 3.2 of the European Radio Equipment Directive (RED). [29]

The requirements of the RED are listed in Article 3 [1]. Article 3.2 states: "*Radio equipment shall be so constructed that it both effectively uses and supports the efficient use of radio spectrum to avoid harmful interference* [1]". From the manufacturer's point of view, the requirement might be very ambiguous as to how it could be fulfilled. For this very reason, ETSI has prepared this harmonised standard to harmonise the used methodology to reach the common goal.

The harmonised standard includes test methods for both the MAC layer and the physical layer. The MAC layer test methods include channel access tests for both random and scheduled access manner in both FT and PT operation modes. The physical layer tests are not included in this thesis, since it is up to the implementer of the physical layer to ensure that the transmitter and receiver operate according to the requirements of the regulations and the standard.

For any radio device implementing the DECT-2020 NR standard, to fully conform with the requirements of Radio Equipment Directive (RED) 2014/53/EU, it must comply with the requirements of the harmonised standard where applicable, i.e., depending on whether a device supports FT, and PT mode, and scheduled data transfer.

In this thesis, the channel access tests in a random-access manner are conducted against an implementation of DECT-2020 NR made by Wirepas Ltd. A common test setup is built for all test cases, and the procedure of all its parts is documented in paragraphs 5.3 and 5.4. All the steps and their purposes are explained to give a detailed view of the process.

5.2 Common test setup

For the ETSI EN 301 406-2 [29] channel access tests, a common physical test setup is built. The setup is a modified version of the reference setup shown in the harmonised standard.

The equipment used:

- Signal generator: N5182A MXG Vector Signal Generator [31]
- Spectrum analyser: N9320A RF Spectrum Analyser [32]
- EUT and Companion device: nRF9161 DK (Development Kit) [33]
- Power splitter: ZN2PD2-50-S+
- Directional coupler: ZGBDC20-33H-S+

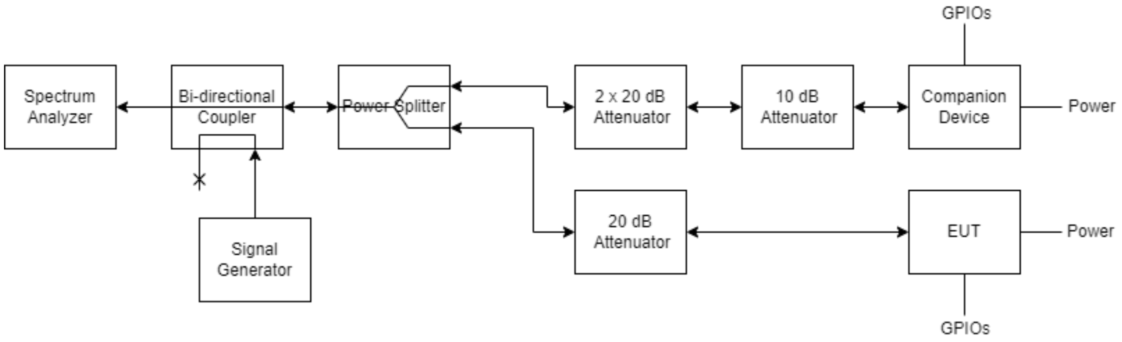


Figure 5.1. *Common test setup for channel access tests.*

In this setup, only the companion device or the signal generator is used at a time, depending on whether FT or PT mode tests are conducted. The companion device is a tester device implementing FT mode functionality which instructs the EUT in the PT mode tests.

The attenuation of the power splitter and directional coupler is measured at each input and output while having the loose ends terminated, and the attenuators are considered to have their nominal levels of attenuation.

The used cables are considered to have a diminishingly low attenuation and are not individually measured. The attenuation from each input to others is calculated using the measured and specified values. The attenuations between each input are thus an approximation. The attenuation values between different inputs are shown in the table below.

Table 5.1. *Approximate attenuation between different input-output combinations, hyphen indicating the same input as above.*

Input	Output	Attenuation (dB)
EUT	Companion device	~100 dB
Spectrum Analyser	Companion device	~55 dB
-	EUT	~25 dB
Signal generator	Companion device	~75 dB
-	EUT	~45 dB

The target and requirement for the setup is to have the path between the EUT and companion device have a high attenuation, while still being able to detect and distinguish the transmissions of both devices [29]. This is achieved by using the attenuators and utilising the isolation of the power splitter. The high attenuation makes the radio devices consistently use the maximum possible transmission power for unicast transmissions, which will prove helpful when analysing and identifying the transmissions between the devices.

The signal generator in this setup is used to produce a wideband AWGN interference signal, which is used for testing the FT mode. The signal generator is unused when conducting PT mode tests.

5.2.1 Signal generator

In testing, a signal generator can be used to transmit arbitrary signals. These signals can be anything from known signals that contain a specific data packet to an interference signal used to mimic channel traffic.

Although possible, using a signal generator to transmit a known packet as an arbitrary signal for protocol testing is not viable, since the signal content will be constant. Using an actual standard compliant signal is more applicable when it is used to monitor the physical properties of a signal waveform. A more usable purpose for a signal generator is to generate interference.

The signal generator in combination with the spectrum analyser can also be used to measure the attenuation between different input–output combinations for a physical testing setup. For example, the attenuation from a tester device to the input of an EUT.

5.2.2 Spectrum analyser

Generally, a spectrum analyser is used to monitor the spectrum content of RF signals. The spectrum analyser monitors the power of a signal as a function of frequency in real time.

For testing purposes, the spectrum analyser (SA) can be used to observe the signals transmitted by the equipment under test (EUT). The spectrum analyser does not provide any bit level information but can be used for detecting power levels and timing of transmissions by using the analyser in zero-span mode.

Zero-span measurement

A zero-span measurement is a type of measurement that can be used to monitor a single frequency over time. With zero-span, the measured power is displayed as a function of time. In this type of measurement, the local oscillator is fixed to a specific frequency. The signal power is measured from the configured resolution bandwidth (RBW) at the centre frequency. The zero-span measurement is useful for measuring the power or detecting time-varying or non-continuous signals. [34]

The main parameters affecting the results of a zero-span measurement are the sweep time, resolution bandwidth and the detector type. The resolution bandwidth determines how wide input filter is used for measuring the input signal. The value of this parameter should be chosen according to the bandwidth of the measured signal. The values for RBW are usually pre-defined, having values of 3 and 10 multiplied by different magnitudes of 10 [32]. For getting accurate power measurements, a resolution bandwidth should be chosen to be wider than the measured signal bandwidth.

The sweep time defines the timespan of a single trace. A single value in a trace is called a trace point, and the number of trace points in a trace is dependent on the used spectrum analyser. The input voltage data from the sweep duration is gathered evenly in bins, each corresponding to one trace point. A detector function is then applied to the data in each of the bins to acquire a value for a trace point, which is then displayed on the spectrum analyser display. [35]

How the trace point value is calculated depends on the used detector mode. For measuring channel power, an RMS (root mean square) detector should be used.

The RMS function calculates the root-mean-square (RMS) value of the input voltage squares it and then divides it by the input impedance (typically 50 Ohm) to get the power value, which is then displayed in dBm [35].

Another useful detector type is the positive peak detector. A positive peak detector takes the highest voltage peak of the voltage data and uses that value for the trace point [35]. A negative peak detector, as the name suggests, does the opposite of a positive peak detector. These detectors are best used for finding the peak power of a signal but do not perform well for measuring the power level of random signals. Combined with measurements using the RMS detector, the positive peak detector can be used to get the PAPR value of a signal.

5.3 Channel Access of a Radio Device in FT mode

5.3.1 Definition

The test requirements are defined in the ETSI EN 301 406-2 harmonised standard [29]. For the FT mode test, the companion device is not used. Instead, the signal generator is used.

In the FT mode test, the Equipment Under Testing (EUT) operates only in FT mode. The FT mode test tests the functionality of cognitive radio spectrum management of the EUT, i.e., to automatically detect which resources are in use by other devices and which ones it can operate on without causing harmful interference to other users.

The operating channel selection procedure begins with the EUT initiating a background scan. During the scan, the EUT should categorise all measured sub-slots into three different states, ‘free’, possible’ or ‘busy’ according to the thresholds defined in the core specification [18]. The scan measures the RSSI-1 value of each sub-slot in a frame, possibly from multiple DECT frequency channels and determines the channel statuses according to those values.

The sub-slot statuses steer the RD in FT mode to select a set of sub-slots it uses as its operating channel. The term, “operating channel” thus refers to the whole resource allocation formed by the chosen sub-slots. The operating channel defines the resources on which the device in FT mode is allowed to transmit its beacon messages and which it is allowed to announce as random-access or scheduled-access resources. Utilising the background scan ensures that the EUT will choose its operating channel such that no other nearby RDs are operating on the resources, to avoid interference.

To test the functionality, an interference signal is used to mimic traffic on a pre-defined set of frequency channels. The goal of the test is to ensure that the EUT will not choose its operating channel from among the channels under the interference.

A table showing the test procedure is shown below. The table shows only the mandatory checks to be performed as well as the related verdict for the test, with **F** indicating **fail** if the check is true, and a pass if the check is false.

Table 5.2. *FT mode test procedure, checks must be false to reach a positive verdict.*

Step	Procedure	Ref. Step	Verdict
1	The interference signal is adjusted to cover the absolute channels 1657 – 1667.	1	-
2	Power on the EUT.	2	-
3	EUT performs operating channel selection according to ETSI TS 103 636-4, clause 5.1.2.	2	-
4	**Check:** Does the EUT transmit on any of the absolute channels 1657 – 1667?	3	F
5	Power off the EUT.	4	-
6	The interference signal is adjusted to cover the absolute channels 1669 – 1677.	1	-
7	Repeat steps 2 – 3.	2	-
8	**Check:** Does the EUT transmit on any of the absolute channels 1669 – 1677?	3	F

The Ref. Step column in Table 5.2 refers to the corresponding test procedure step defined in ETSI EN 301 406-2 [29]. The absolute channels mentioned in Table 5.2 are defined in part 2 of the DECT-2020 NR specification [30].

5.3.2 Test configuration

In the test environment, the EUT in FT mode is configured to transmit the network beacon on a 1-second periodicity, having the network channel set to channel 1659. The network beacon is only transmitted if the network channel contains enough ‘free’ sub-slots.

The cluster beacon transmission is set to an 8-second periodicity, and it is transmitted on the operating channel selected by the EUT. The beacons are transmitted only after the EUT has chosen a suitable operating channel. Both beaconing messages are transmitted at the highest possible transmission power level in its device class (19 dBm) [30]. The configuration is collected in Table 5.3 below.

***Table 5.3.** Configuration of transmitted beacon messages.*

Message	**Periodicity**	**Channel**	**Tx power**
Network beacon message	1 s	1659	19 dBm
Cluster beacon message	8 s	Any, except the network channel	19 dBm

5.3.3 The AWGN interference signal

The channel access tests specify an AWGN interference signal with specific requirements to be used in the tests:

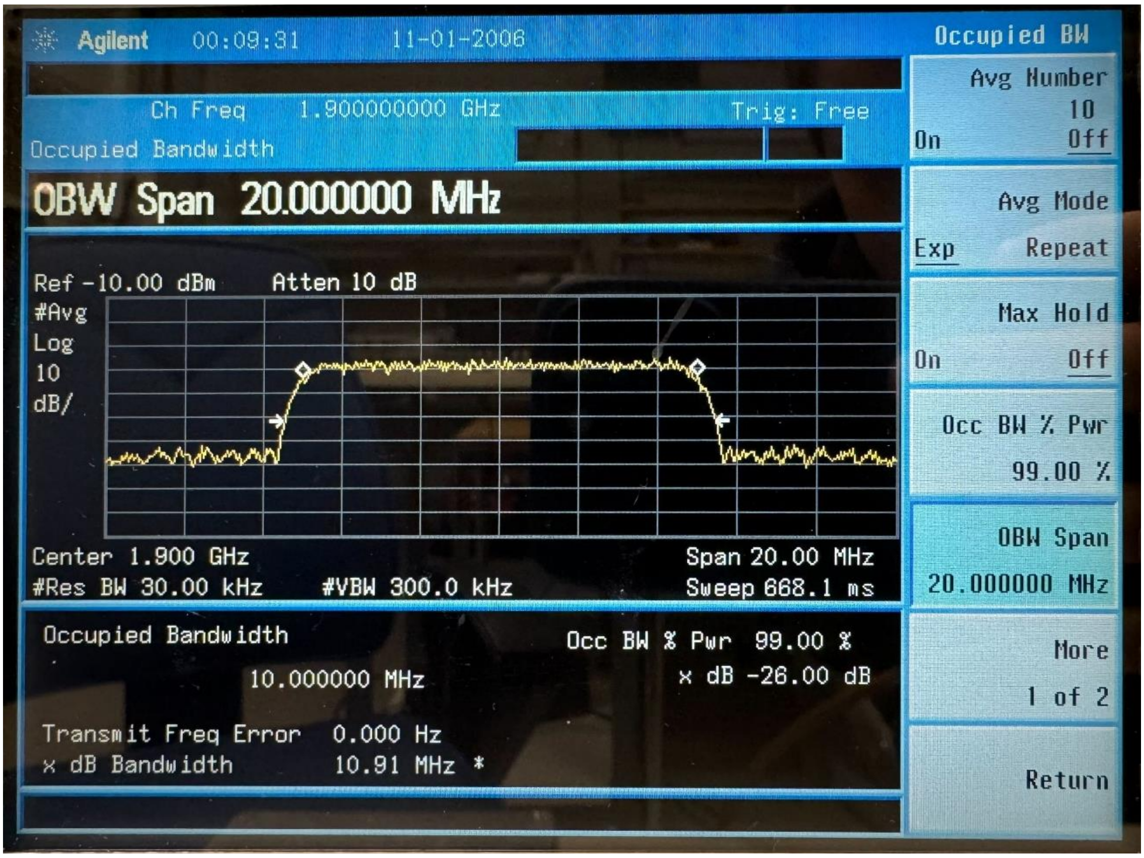
"The inference signal used in the channel access tests described in clauses 5.6.2 to 5.6.5 shall be a band-limited noise signal with a 100 % duty cycle. The 99 % bandwidth (the bandwidth containing 99 % of the power) of this inference signal shall be able to cover 50 % of the applicable operating band given in Table 1. The power difference between the lowest and highest nominal channel shall be in maximum 4 dB." [29].

The operating band defined in the harmonised standard refers to the DECT-2020 NR operating band 1 [29]. The band spans from $1880\ \mathrm{MHz}$ to $1900\ \mathrm{MHz}$, thus having a $20\ \mathrm{MHz}$ bandwidth and making the 99% bandwidth requirement $10\ \mathrm{MHz}$.

The AWGN interference signal used in the FT mode tests is created as a complex Gaussian-distributed random signal with a variance of 1 and filtered to half bandwidth. The signal is created as an arbitrary signal and the values are written to the signal generator memory using PyVISA and SCPI commands [36]. The AWGN interference signal is outputted from the signal generator with a sampling rate of $20\ \mathrm{MHz}$ to reach the required signal bandwidth of $10\ \mathrm{MHz}$.

The signal generator indefinitely repeats the signal to reach the required duty cycle of 100%, to fully occupy the frequency channel in time. This results in that the AWGN signal may not be purely random but has been created to be long enough to have enough variation.

The occupied bandwidth i.e., the 99% bandwidth has been measured to be $10.0\ \mathrm{MHz}$ and is sufficiently flat on the $10\ \mathrm{MHz}$ bandwidth, having a maximum of $0.6\ \mathrm{dB}$ difference in the average power when measured between the edge channel and the middle channels in this setup.



Agilent 00:09:31 11-01-2006

Ch Freq 1.900000000 GHz Trig: Free

Occupied Bandwidth

OBW Span 20.000000 MHz

Ref -10.00 dBm Atten 10 dB

#Avg
Log
10
dB/

Center 1.900 GHz Span 20.00 MHz

#Res BW 30.00 kHz #VBW 300.0 kHz Sweep 668.1 ms

Occupied Bandwidth 10.000000 MHz

Occ BW % Pwr 99.00 %

x dB -26.00 dB

Transmit Freq Error 0.000 Hz

x dB Bandwidth 10.91 MHz *

Figure 5.2. *Measured occupied bandwidth, i.e., the 99% bandwidth of the AWGN interference signal.*

The requirements for the AWGN interference signal and the achieved values are gathered in Table 5.4. The values in the table are sufficient for the test use.

Table 5.4. *AWGN interference signal requirements along with used values for FT mode testing [29].*

Parameter	Requirement in EN 301 406-2	Measured value
Duty cycle	100%	100%
99% bandwidth	50% of the operating band	10.0 MHz
Max power difference	4 dB	0.6 dB

The power level of the AWGN signal

The power of the AWGN interference signal at the EUT input needs to be set $3\ \mathrm{dB}$ above the threshold to reach the 'busy' channel status measured from the transmission bandwidth as specified in the harmonised standard [29]. The test setup will have attenuation from the path from the signal generator to the EUT input as shown in Table 5.1. Additionally, the modulating signal will spread the power on the transmission bandwidth.

These factors are considered, and the output power level of the signal generator is set accordingly.

The ‘busy’ channel status is reached when the measured RSSI-1 (Received Signal Strength Indicator) value in the EUT input exceeds the $RSSI\_THRESHOLD\_MAX$ value. The value is defined as: $RSSI\_THRESHOLD\_MAX = -52\ \mathrm{dBm} - P\_TX\_MAX$ [18], where the P_TX_MAX is the maximum transmission power of the RD conducting the measurement.

The threshold for the ‘busy’ sub-slot is defined lower for devices that can transmit with a higher power since a device capable of transmitting with a higher power can interfere on a larger area and thus needs to take the more distant and less powerful devices into consideration.

For a sub-slot to be determined ‘busy’, i.e., to exceed the threshold $RSSI\_THRESHOLD\_MAX$ by an RD having a maximum transmission power level of $19\ \mathrm{dBm}$, the RSSI-1 power level, which is measured from the transmission bandwidth of the EUT (the bandwidth containing OFDM subcarriers + the zero-frequency bin) has to be over $-52\ \mathrm{dBm} - 19\ \mathrm{dBm} = -71\ \mathrm{dBm}$, independent of the used transmission bandwidth [30]. Depending on the transmission bandwidth of the EUT (in this case: $57 * 27\ \mathrm{kHz} = 1.539\ \mathrm{MHz}$), the AWGN interference signal power spectral density at the EUT input needs to be $3\ \mathrm{dB}$ above:

$$-71\ \mathrm{dBm} - 10 * \log_{10}(1539000\ \mathrm{Hz}) \approx -132.9\ \mathrm{dBm/Hz}.$$

Thus, to reach the required interference level at the EUT input, the signal generator output power level shall be set to at least:

$$-132.9\ \mathrm{dBm/Hz} + 10 * \log_{10}(99\%\ \mathrm{BW}) + VSG\_EUT\_attenuation + 3\ \mathrm{dB} = -14.9\ \mathrm{dB},$$

where the 99% BW is the occupied bandwidth of the AWGN interference signal, measured in Figure 5.2 and show in Table 5.4, and the $VSG\_EUT\_attenuation$ is the attenuation between the signal generator and the EUT, indicated in Table 5.1.

When an interference signal with the indicated power spectral density level is applied to a set of channels, those channels will be considered to have interference sufficient to render all of the sub-slots within the channels “busy” during a background scan, i.e., block them from any use.

5.3.4 Spectrum analyser measurement

The transmissions of the EUT are monitored using a spectrum analyser. The harmonised standard defines a set of spectrum analyser settings for monitoring a single channel. These settings and corresponding ones used in the test setup are collected to the Table 5.5 below.

Table 5.5. *Required and used spectrum analyser measurement settings [29].*

Parameter	**Requirement in EN 301 406-2**	**Used value**
Centre frequency	Channel centre	Channel centre
Frequency span	0 Hz	0 Hz
RBW	~50% of 1.728 MHz	1 MHz
VBW	>RBW	3 MHz
Detector	RMS	RMS
Sweep time	Sufficient to cover the period over which the transmission is spread out.	8 s
Number of sweep points	Sufficient to meet the maximum measurement uncertainty of 5% for the period to be measured.	461
Trace mode	Clear/Write	Clear/Write
Trigger	Video	Free run

The spectrum analyser centre frequency is set to correspond to the channel centre frequency, span is set to zero for a zero-span measurement. The sweep time is set to 8 seconds to be able to fully capture one cluster beacon period in one trace, i.e., to ensure that a possible cluster beacon transmission can be detected in a trace. The number of sweep points is a constant value which cannot be changed and is a characteristic of the spectrum analyser [32]. The trigger is set to free run to be able to capture traces from all of the channels, even those not containing any transmissions.

The test measurements are conducted by consecutively measuring each of the DECT-2020 NR channels included in the currently interfered channel set, using the settings defined in the table above. The traces acquired from the spectrum analyser are saved and further analysed for defining verdict.

5.3.5 Test procedure

The tests are conducted on the DECT operating band 1 which is located at 1880 – 1900 MHz spectrum [28]. The operation with the nominal channel bandwidth of 1.728 MHz is restricted to 11 absolute channels, each separated by 2 absolute channel numbers, i.e., 1657, 1659, 1661… 1677. The nominal centre frequencies for channels in band 1 are calculated as:

$$f_n = 450.144\text{ MHz} + n * 0.864\text{ MHz} \tag{5.1}$$

where n is the absolute channel number. [30]

For the testing purposes, the nominal DECT-2020 NR channels are divided into two sets, where one set of channels is interfered with a wideband AWGN signal at once while having the other channels free from interference. The first set of channels is chosen to include 6 of the lowest channels, and the second set the remaining 5 channels.

The bandwidth of the interference signal relative to the channels is shown in the Figure 5.3 below.

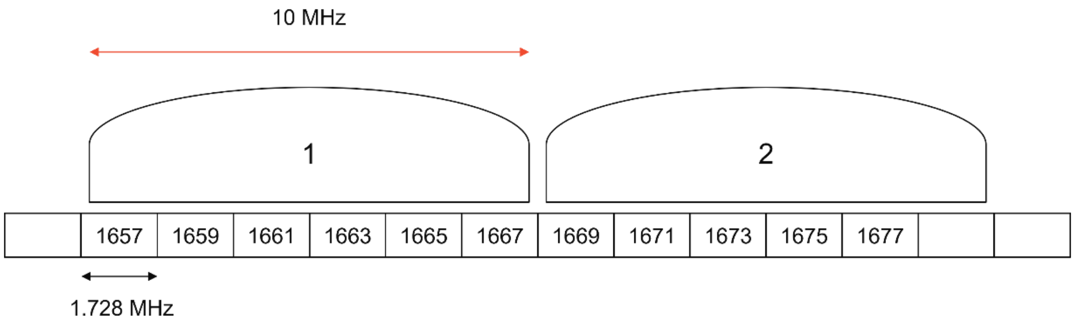


***Figure 5.3.** Interference signal bandwidth relative to a set of DECT-2020 NR channels.*

The AWGN interference signal is applied on a channel set by setting the carrier frequency of the signal generator to correspond the interference centre frequency. The first channel set has the channels numbered: 1657, 1659, 1661, 1663, 1665, and 1667. These channels with a bandwidth of 1.728 MHz are directly next to each other and have a total bandwidth of 10.368 MHz. These channels include a guard band on both sides, meaning that the nominal bandwidth is larger than the actual transmission bandwidth. The occupied bandwidth of the interference signal is thus slightly narrower than the first set of channels. This makes the edge channels have slightly less interference than the channels in the middle. It is still sufficient to set the carrier frequency of the interference signal to the middle of the channel set 1, i.e., to the frequency of the absolute channel number 1662 ($1886.112\ \mathrm{MHz}$), since the power difference of the interference signal measured between the edge channel and middle of the signal is smaller than the used $3\ \mathrm{dB}$ power margin.

The second channel set contains 5 channels: 1669, 1671, 1673, 1675, and 1677, having a total bandwidth of $8.64\ \mathrm{MHz}$, which is lower than the interference bandwidth. The interference signal should be centred such that it does not interfere with the channels not belonging to the current set. By setting the centre of the interference signal to the absolute channel 1674 ($1896.480\ \mathrm{MHz}$), all the channels belonging to the upper set (set 2) will be interfered and some power will leak out of the $20\ \mathrm{MHz}$ DECT band. In a conducted test environment, it is not a problem.

The channel sets are gathered in Table 5.6 below, indicating the interfered channels and the centre frequency of the noise signal.

Table 5.6. *DECT-2020 NR channels covered by the interference signal and its respective centre frequency.*

Set	Interfered channels	AWGN interference signal centre frequency
1	1657, 1659, 1661, 1663, 1665, 1667	1886.112 MHz
2	1669, 1671, 1673, 1675, 1677	1896.480 MHz

Test procedure

The test procedure is initiated by setting the signal generator to output the interference signal on the first channel set. The EUT is then powered on or reset. After powering on, the EUT should measure the RSSI-1 values of sub-slots, and determine them as “free”, “possible”, or “busy”. The EUT in FT mode should select its operating channel from the set of un-interfered channels and begin to transmit cluster beacons on the chosen channel as a part of normal FT mode operation [18].

If the pre-configured network channel is not in the set of currently interfered channels, the EUT may begin transmitting the network beacon on that channel. The EUT is allowed to transmit the cluster beacon messages even if the network beacon cannot be transmitted on the network channel.

After the EUT has chosen its operating channel, the spectrum analyser is used to measure each DECT-2020 NR channel using the configuration defined in paragraph 5.3.4. The acquired spectrum analyser traces are saved for further analysis.

For the second test round, the interference is moved over the second set of channels and the EUT is reset, and the test is repeated.

5.3.6 Result analysis and verdict

To reach a positive verdict, all the channels under the influence of the interference signal must indicate no transmission on them by the EUT. This can be visually checked from the acquired traces. It can be seen as a trace having no power spikes exceeding a threshold which would indicate a transmission on the current channel. It can be additionally verified that the EUT has chosen a ‘free’ channel for its operating channel, although it is not mandatory from the harmonised standard point of view [29].

It should be noted that the RMS level of the spectrum analyser trace points containing the transmissions does not directly correspond to the RMS level of the transmission power of the EUT. The measured RMS values are affected by several factors, which can be individually derived to choose a suitable threshold.

Defining a threshold for detected transmission

To derive the threshold for an RMS measurement, 3 factors are identified to have an effect on the displayed power level, the resolution bandwidth, sweep time, and the path loss of the signal. The threshold should be derived by starting from the nominal maximum RD Tx power and deducting the factors lowering the power value.

A device transmitting with a maximum power of $19\ \mathrm{dBm}$ will have its RMS power around $19\ \mathrm{dBm}$, meaning the peak can be even higher.

The path from the EUT to the spectrum analyser will introduce attenuation due to attenuators, and insertion losses of components. This value can be used as it is. An approximation of the value is calculated and shown in Table 5.1.

When the resolution bandwidth of the spectrum analyser is lower than the transmission bandwidth of the signal, the full power of the signal cannot be measured, and the spectrum analyser will indicate a lower power level. If the signal spectrum is sufficiently flat, i.e., the power is spread evenly across the whole transmission bandwidth, an approximation of the reduction in measured power caused by the lower resolution bandwidth can be derived by linearly scaling the power from the transmission bandwidth TXBW to the resolution bandwidth RBW:

$$10 * \log_{10}(\mathrm{RBW}/\mathrm{TXBW}). \tag{5.2}$$

In reality when the signal spectrum is not perfectly flat, the reduction due to the low resolution bandwidth will be less.

When RMS averaging is used for measuring the signal power and the signal length is shorter than the integration time of one spectrum analyser trace point, most of the values for calculating the RMS value are noise, while only a fraction comes from the actual signal. This significantly reduces the displayed power value. It can be corrected by knowing the exact bin length from which the values for a trace point are calculated and the signal length while assuming noise as near zero when compared to the signal power. This is done with the following formula:

$$10 * \log_{10}\left(t_{sig}/\mathrm{t_{bin}}\right), \tag{5.3}$$

where t_{sig} is the signal length and t_{bin} is the time for a single bin in seconds, and assuming that the signal is located fully within one trace point.

Calculation of the threshold value

In the protocol implementation, a network and cluster beacon message are both transmitted with a signal length of 3 sub-slots. When constructing the physical signal according to the standard [37], the signal will consist of 1048 samples transmitted at a $1.728\ \mathrm{MHz}$ sampling rate. The signal length in seconds can thus be calculated to be:

$$t_{sig} = \frac{1048}{1.728\ \mathrm{MHz}} = 606.48\ \mathrm{\mu s}.$$

For an 8-second sweep, the time from which the trace point value is calculated is significantly longer than the signal length. The bin length is calculated by dividing the sweep time by the number of trace points, which for the used spectrum analyser is 461 [32]. This makes one trace point calculate its value from a timespan of:

$$t_{bin} = \frac{8\ \mathrm{s}}{461} = 17.4\ \mathrm{ms}.$$

By fitting the values t_{sig} and t_{bin} to the formula 5.3, the reduction in the displayed power due to the sweep time of the spectrum analyser results in a factor of:

$$10 * \log_{10}\left(t_{sig}/\mathrm{t_{bin}}\right) = -14.6\ \mathrm{dB}.$$

When using a $1\ \mathrm{MHz}$ resolution bandwidth (RBW) and having the transmission bandwidth (TXBW) at $1.539\ \mathrm{MHz}$, the reduction in the displayed power level due to the lower resolution bandwidth may be calculated with the formula 5.2 as follows:

$$10 * \log_{10}(\mathrm{RBW}/\mathrm{TXBW}) = -1.9\ \mathrm{dB}.$$

Using the acquired values, the maximum displayed power level for the RMS measurements can thus be calculated to be approximately:

$$19\ \mathrm{dBm} - 14.6\ \mathrm{dB} - 1.9\ \mathrm{dB} - 25\ \mathrm{dB} = -22.5\ \mathrm{dBm}.$$

To determine the threshold for ensuring that a transmission is occurring on the monitored channel and not on any adjacent channel, the harmonised standard requirement for transmitter unwanted emissions in out of the band domain is utilised. The requirement shows that the emission limit within the bandwidth of an adjacent channel is $-10\ \mathrm{dBc}\ @1\ \mathrm{MHz}$ [29]. To ensure that a transmitter staying barely within the limits will not exceed the threshold, a margin is applied.

By taking the approximate maximum displayed power level, subtracting the emission limit, and adding some margin, **the threshold is chosen to be $\mathbf{-30\ dBm}$**. Channels indicating measured values above this threshold can thus be considered to have transmissions on them by the EUT.

Channel traces

The traces acquired from conducting the FT mode tests against an implementation of DECT-2020 NR are shown below in Figure 5.4, Figure 5.5, Figure 5.6, and Figure 5.7.

For the first test case, channel set 1 is being interfered, having the interference located as shown in Figure 5.3 and on channels indicated in Table 5.6. Both the expected ‘free’ and ‘busy’ channel traces have been acquired to verify the correct behaviour of the EUT.

Test case 1

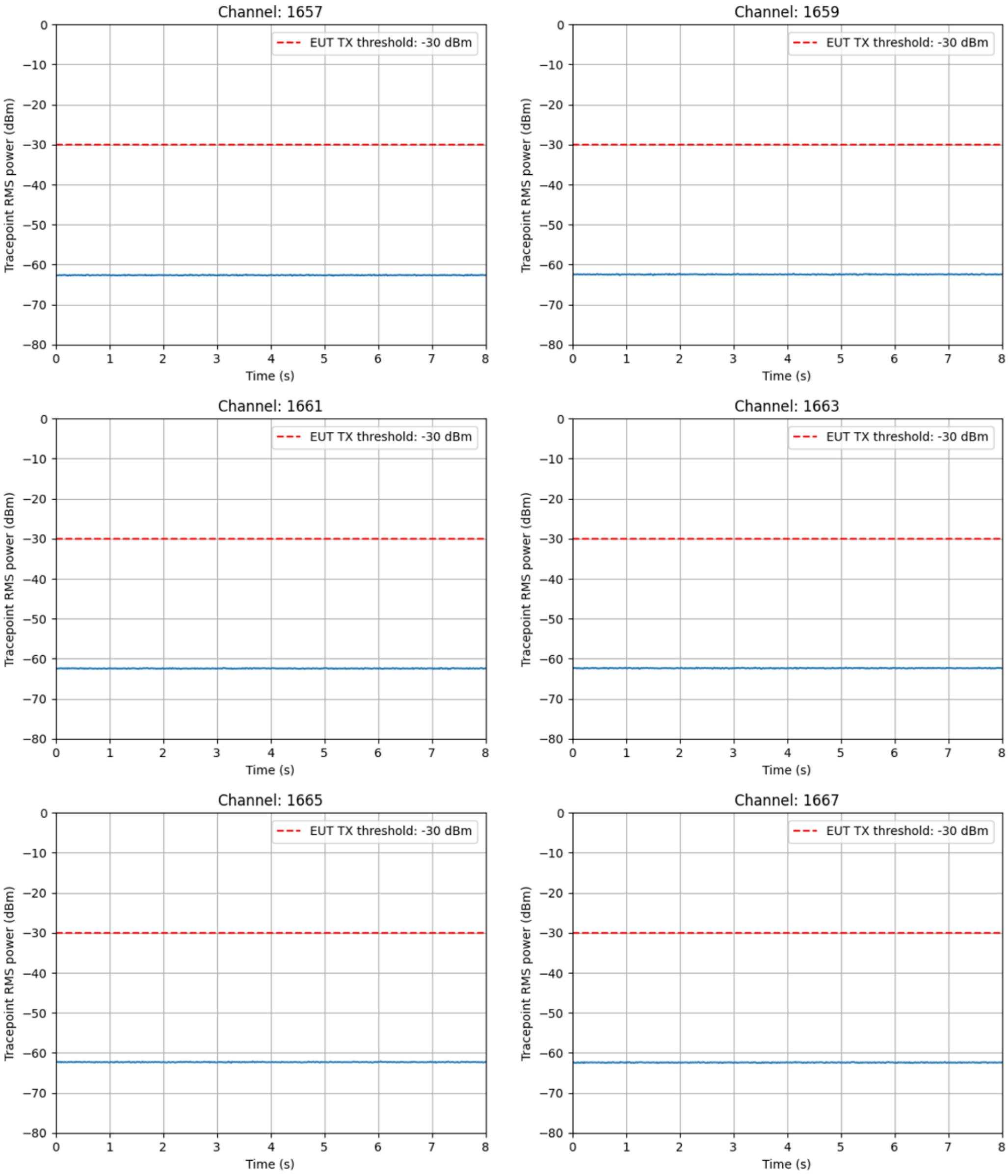


Figure 5.4. *Zero-span measurement traces from channels affected by interference, test case 1.*

The spectrum analyser traces in Figure 5.4 indicate no transmissions on the interfered channels. The EUT thus can be confirmed to correctly avoid the channels on which it detects transmissions or interference. This can be considered as correct behaviour, passing the test case.

The rest of the channels (set 2) are free from interference and are allowed to contain transmissions on them by the EUT in FT mode. Since the application is configured to have the network channel on DECT channel 1659, the network beacon will not be transmitted since its channel is considered ‘busy’. The traces from channels on which transmissions are allowed are shown below.

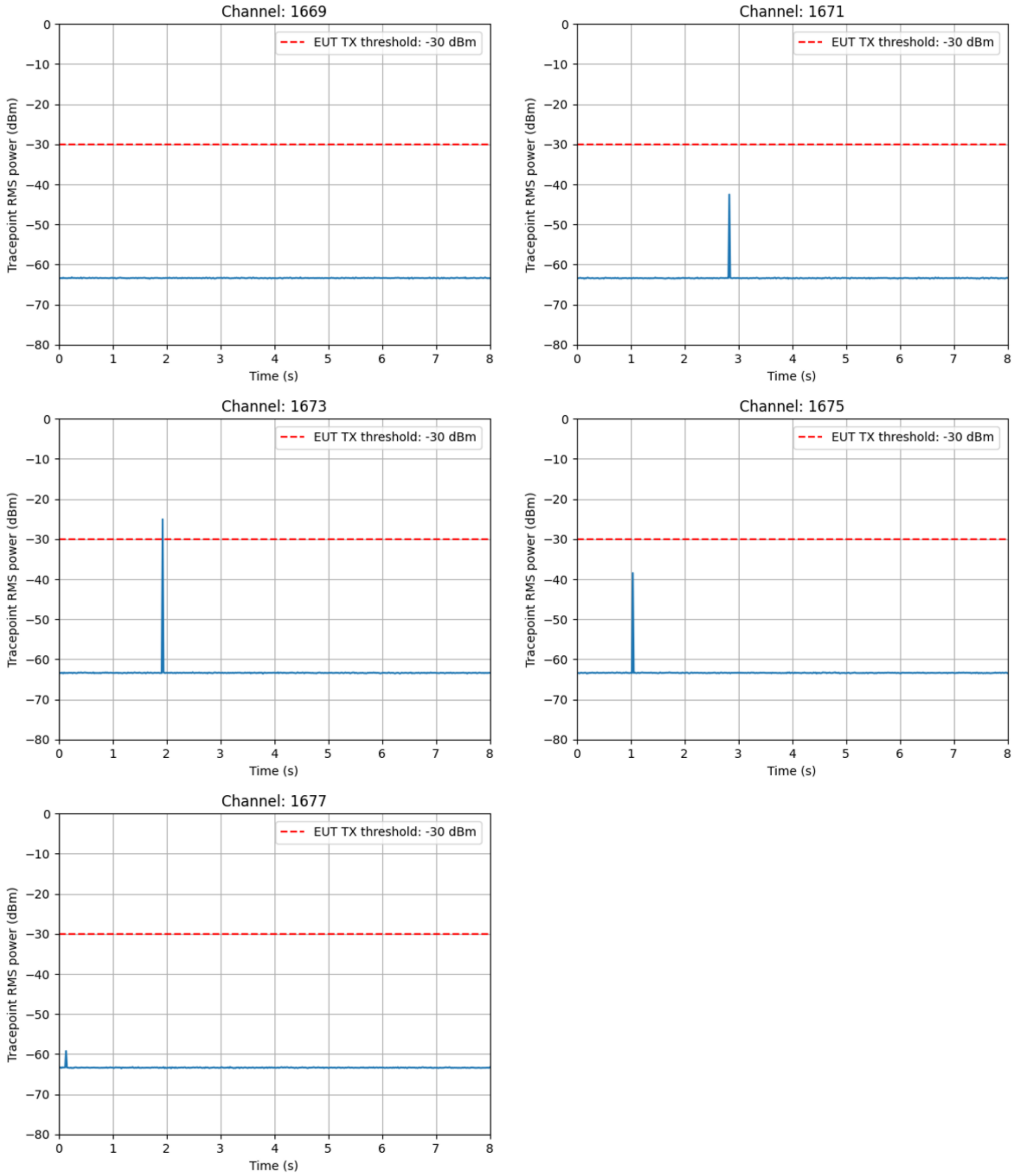


Figure 5.5. *Zero-span measurement traces from channels not affected by interference, test case 1.*

From the traces in Figure 5.5, it is possible to detect the presence of the cluster beacon as the highest power spike exceeding the threshold on channel 1673, which occurs once every 8 seconds. Lower power spikes can be seen on the adjacent channels appearing due to out-of-band emissions.

Test case 2

The second test case has the interference applied on channel set 2, as depicted in Figure 5.3. The acquired spectrum analyser traces are shown below.

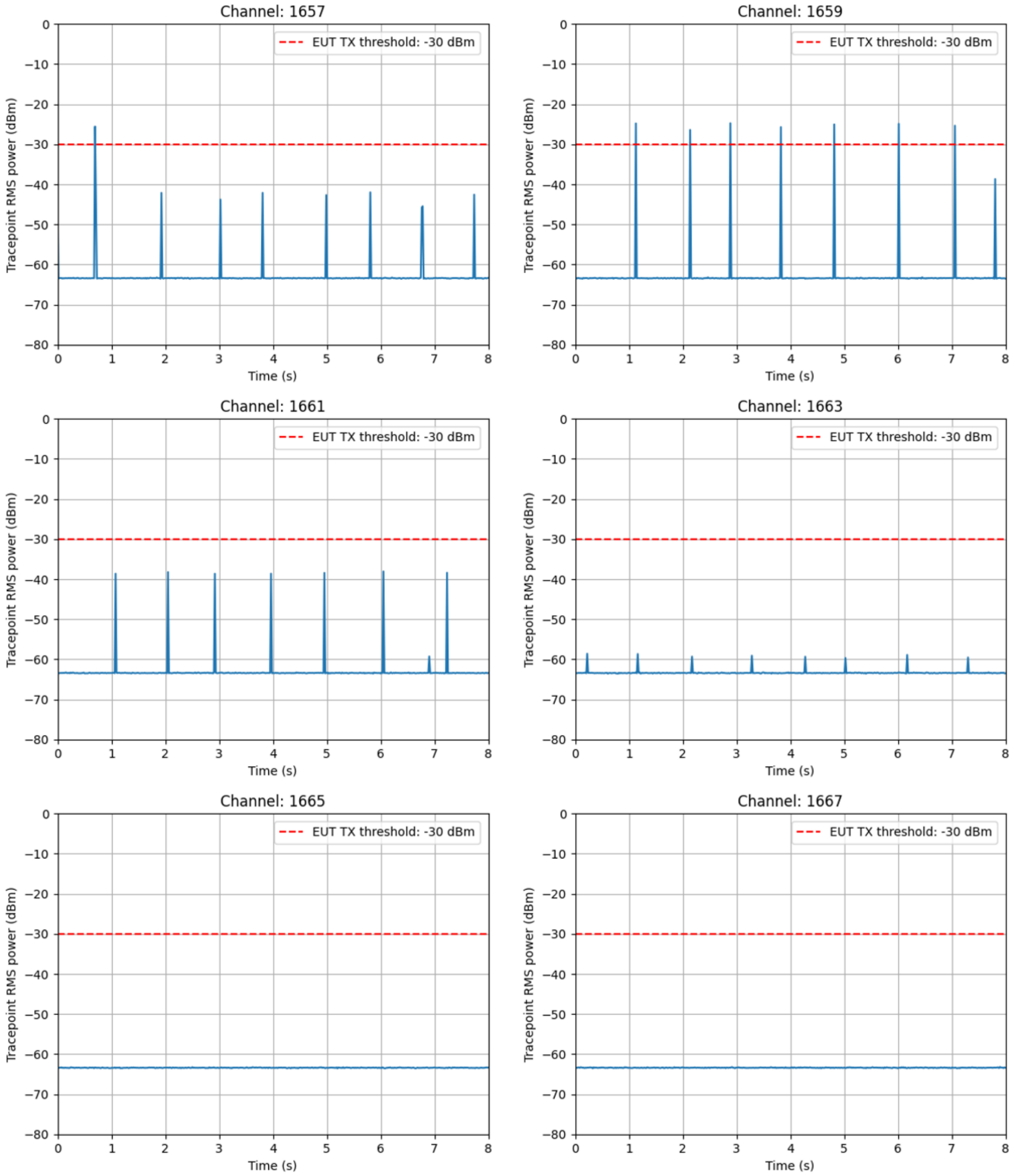


Figure 5.6. *Zero-span measurement traces from channels not affected by interference, test case 2.*

In Figure 5.6, the network beacon occurring at 1-second intervals can be detected on channel 1659, and the cluster beacon on channel 1657 with 8-second periodicity. These power spikes exceed the threshold to indicate a transmission by the EUT is occurring on the observed channel. This is allowed behaviour since the channels are free from any other traffic or interference. The channels containing transmissions additionally show power spikes due to leakage from transmissions occurring on neighbouring channels, but they are ignored due to them being below the threshold.

The traces from channels affected by the AWGN interference signal in the test case 2 are shown below.

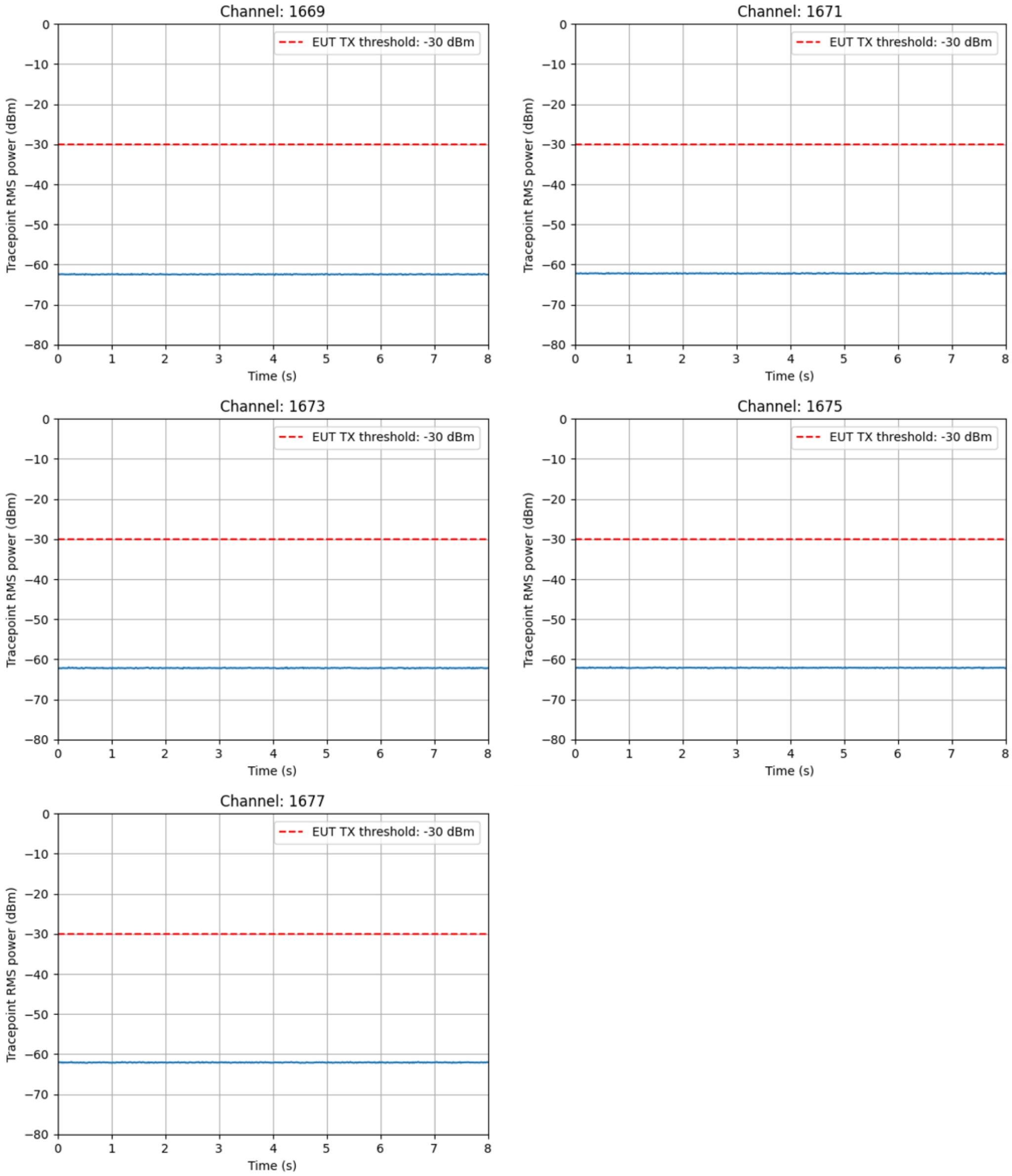


Figure 5.7. *Zero-span measurement traces from channels affected by interference, test case 2.*

As seen in Figure 5.7, all the channels having interference applied on them show no transmissions on them by the EUT.

Verdict: The spectrum analyser traces shown in the figures above show the desired result. The implementation can thus be confirmed to comply with the regulatory channel access requirements when operating in FT mode. Further test cases could be made for this test by experimenting with varying sets of interfered channels.

5.4 Channel Access of a Radio Device in PT mode and Random Access

5.4.1 Definition

The test requirements are defined in the ETSI EN 301 406-2 harmonised standard [29]. The PT mode tests are conducted with the common test setup shown in Figure 5.1. In this test, the signal generator is unused and can be switched off. Now, the companion device is used for this test.

In the PT mode tests the EUT operates only in PT mode. The PT mode tests of the harmonised standard initially require the ability of the EUT to perform association and begin communication on random-access resources announced by a companion device (CD) operating in FT mode. This could be considered as being an initial test case, leading to the initial state for the other test cases.

The purpose of the harmonised standard tests for PT mode is to verify the behaviour of the EUT when it is requested or needs to stop using the radio spectrum for transmission. There are two test cases to be conducted for these purposes. Both tests are initiated from the same state, having performed association, and periodically transmitting to random-access resources announced by the companion device in FT mode.

Initial test case

The initial test case tests the ability of the EUT to only transmit on resources announced by the associated device in FT mode.

Test case 1

The idea of the first test is that the companion device in FT mode will change its operating channel, forcing any associated RD to stop using the previously announced resources, and preferably move to use the resources of the new operating channel.

When the companion device decides to change its operating channel, both the cluster beacon transmissions and random-access resources will be moved to the new operating channel. The companion device informs this to the EUT in the next occurrence of the cluster beacon where it announces that the next cluster beacon will be transmitted to another channel. The next cluster beacon then indicates random-access resources being allocated to the new operating channel.

The target of the test is to verify that the EUT in PT mode will not continue to transmit to the previously announced random-access resources after receiving instruction forcing so. The requirements described in the harmonised standard state that the EUT must cease its transmissions to an operating channel within 10 seconds after receiving an instruction to do so, either because of changing the channel or revoking resources [29].

Test case 2

The second test case tests the behaviour of the EUT in PT mode when it completely loses connection to the RD in FT mode. This kind of scenario could typically be caused due to an RD getting out of range of another RD.

The functionality being tested is the random-access procedure and the validity of the random-access resources. When the EUT cannot receive a random-access response to a transmission because it has either been lost, there was a collision, or the EUT cannot otherwise decode the control information of a random-access response to detect its own short RD ID, the RD should stop using the radio resources within a specified time limit.

In the functionality defined in the core specification, not receiving a random-access response starts a timer. If there are no responses or new random-access resources received within that timer, the RD should stop all transmissions on the attempted random-access resources. The RD then considers the connection to be lost, leading it to release its association with the RD in FT mode. [18]

While not receiving any response from the companion device, the EUT may attempt to perform retransmissions according to the random-access procedure, to the previously received random-access resources.

The harmonised standard requires that the EUT in PT mode must cease its transmissions on the operating channel within 30 seconds after it loses connection with the companion device. The time instance at which the connection is considered lost is defined as the end of the 10th transmission of the EUT after removing the companion device. [29]

The test procedure for the test cases is shown in Table 5.7 below. The verdict indicating **P** means that a test will **pass** if the check is true or **fail** if the check is false.

***Table 5.7.** PT mode test procedure.*

Step	Procedure	Ref. step	Verdict
1	Power on the companion device. (RD FT)	-	-
2	Companion device performs operating channel selection according to ETSI TS 103 636-4 [18], clause 5.1.2.	-	-
3	The companion device begins transmitting cluster and network beacons.	2	-
4	Power on the EUT. (RD PT)	-	-
5	EUT performs the association procedure towards the companion device according to ETSI TS 103 636-4 [18], clause 5.8.	-	-
6	**Check:** Does the EUT begin to transmit to the resources announced by the companion device?	2	P
7	Operating channel change is queued by user input.	3	-
8	The companion device indicates in a cluster beacon that the next cluster beacon will be transmitted on a different channel. The companion device shall inform via the control interface once it has changed operating frequency and instructed the EUT.	3	-
9	**Check:** Does the EUT stop all transmissions on the previously used channel within 10 seconds after the companion device changes operating frequency?	4	P
10	Power off the EUT and companion device, then repeat steps 1 – 6 and continue to step 11.	5	-
11	The companion device is powered off, removed, or attenuated significantly for it to lose connection with the EUT.	6	-
12	The EUT transmits 10 times to the previously acquired random-access resources.	7	-
13	**Check:** Does the EUT stop all transmissions within 30 seconds after execution of step 12?	7	P

5.4.2 Test configuration

The companion device is configured to operate as a qualified FT mode tester device, announcing resources for the EUT in PT mode on any of the DECT channels except the network channel, which is only used to transmit network beacons. The companion device is configured to force a cluster channel change from a user input, after which the cluster channel change will be queued, and information will be provided to the EUT in the next occurrence of the cluster beacon message. The companion device will transmit the beaconing messages as defined in Table 5.3.

The EUT is configured to operate in the same network as the companion device. The EUT is set to transmit random application data with a 1-second periodicity to the random-access resources announced by the companion device after the EUT has acquired a route to a sink. The transmissions of the EUT are done with a PHY header format that requires a response from the companion device.

The test setup includes a user interface where the EUT is configured to notify the user when it has a route to sink via GPIO. As instructed in the harmonised standard, the companion device is configured to indicate when it has instructed the EUT to stop using the current channel. Additionally, the companion device indicates the successful reception of a packet via another GPIO to verify that the EUT uses the resources announced by the companion device.

5.4.3 Spectrum analyser measurement

The spectrum analyser is used to capture the traces from which the test verdicts can be deduced. The used spectrum analyser settings are as shown in Table 5.5, and further modified by the parameters defined in this paragraph.

Initial test case

The spectrum analyser may be used to check whether the companion device is responding to the transmissions of the EUT. For this, modified spectrum analyser settings are needed, as shown in Table 5.8.

Table 5.8. *Spectrum analyser parameters for checking transmission-response pair.*

Parameter	**Requirement in EN 301 406-2**	**Used value**
Sweep time	Sufficient to cover the period over which the transmission is spread out.	2 ms
Trigger	Video	Video

Test case 1 & 2

For the test cases 1 and 2, only the spectrum analyser sweep time is modified. By having a longer sweep time the results will prove to be more reliable.

Table 5.9. *Spectrum analyser parameters for PT mode testing.*

Parameter	**Requirement in EN 301 406-2**	**Used value**
Sweep time	Sufficient to cover the period over which the transmission is spread out.	50 s

5.4.4 Test procedure

Both the companion device and the EUT are powered on. The EUT in PT mode should initiate the association procedure based on the beacon messages transmitted by the companion device in FT mode. After a successful association, the EUT should have a route to sink.

When the EUT is confirmed to have a route to the sink, it should begin transmitting data to the random-access resources announced by the companion device. Having the route to the sink and transmitting the data can be externally identified from the GPIOs on both the EUT and companion device. Another method to verify the correct random-access resource use is to observe whether the companion device transmits a response message to the EUT.

To begin any of the tests, the transmissions occurring on the operating channel should be monitored using the spectrum analyser. The operating channel is searched by taking long enough zero-span measurements to cover the periodicity of EUT transmissions. A measurement trace is taken from each possible DECT channel except the network channel and a threshold is applied to verify that a transmission is occurring on the observed channel and not caused by leakage from another channel. After the operating channel is found, the EUT transmissions should be seen as power spikes on the spectrum analyser display.

Initial test case

The GPIOs of both the companion device and the EUT are monitored to verify the use of the correct random-access resources.

OR

A 2-millisecond sweep, triggered by the power level of the EUT transmission is primed. When the sweep is triggered, the spectrum analyser should show the transmissions of both the EUT and companion device, indicating that the EUT uses the correct random-access resources.

Test case 1

The 50-second spectrum analyser sweep is triggered. After an arbitrary number of periodic transmissions by the EUT, the channel change may be triggered on the companion device. The spectrum analyser is allowed to sweep for the whole sweep time. After completing the sweep, the measured trace data is saved for further analysis and defining the verdict.

Test case 2

After the first test case, the new operating channel is selected according to the channel selection rules and thus needs to be searched again. Both devices can be reset for conducting the second part of the test, or the newly picked channel may be used.

In the second test, a 50-second spectrum analyser sweep is triggered. After detecting at least one EUT transmission, the companion device is powered off, causing the EUT to lose its connection to the companion device. The measured trace data from the spectrum analyser is again saved for further analysis.

5.4.5 Result analysis and verdict

To define a verdict, the channel traces are inspected, and the transmissions of both the EUT in PT mode and companion device are identified. In the PT mode tests, a positive verdict is reached when a trace shows that no further transmissions by the EUT are occurring after the defined time limit, and after that, only the noise floor of the spectrum analyser can be seen.

Initial test case

For the initial test case, the transmissions of the EUT are inspected and checked whether the companion device is sending a response, which would indicate that the EUT is using the correct channel resources. An acquired trace of the transmission–response pair of the EUT and companion device is depicted in Figure 5.8 below.

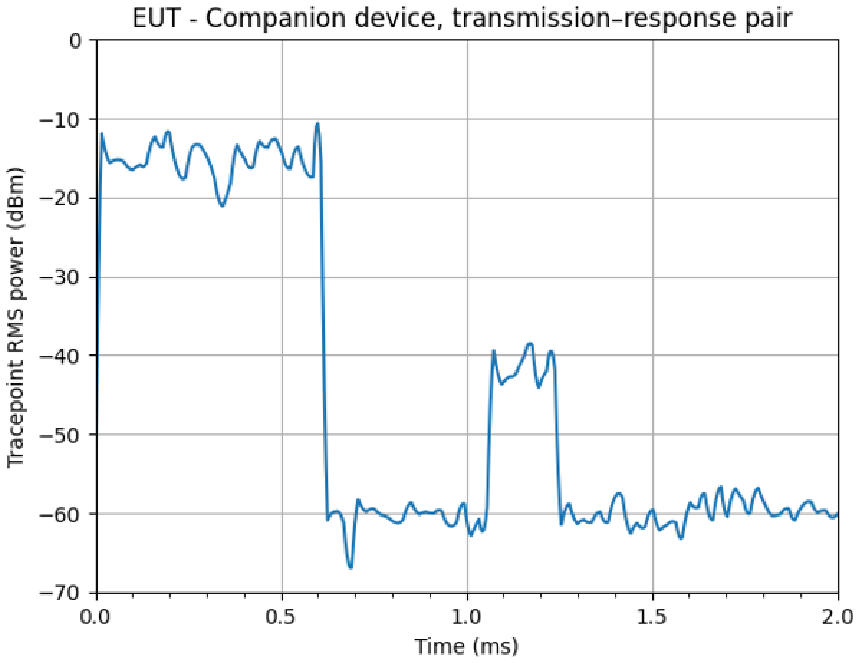


Figure 5.8. *Transmission - response pair of the EUT and companion device.*

The figure above shows that some transmission is followed by another shorter transmission with a lower power level. The power differences indicate that the sources of the transmissions might be different.

As shown in Table 5.1, the EUT has around $30\,\mathrm{dB}$ less attenuation on the path to the spectrum analyser than the companion device, thus the transmissions of the companion device with the same transmission power can be seen as having around $30\,\mathrm{dB}$ lower level.

The transmissions in Figure 5.8 having around $30\ \mathrm{dB}$ power difference can thus be identified as a transmission–response pair of the EUT and the companion device.

Test case 1

The result from the test case 1 is shown in Figure 5.9 below.

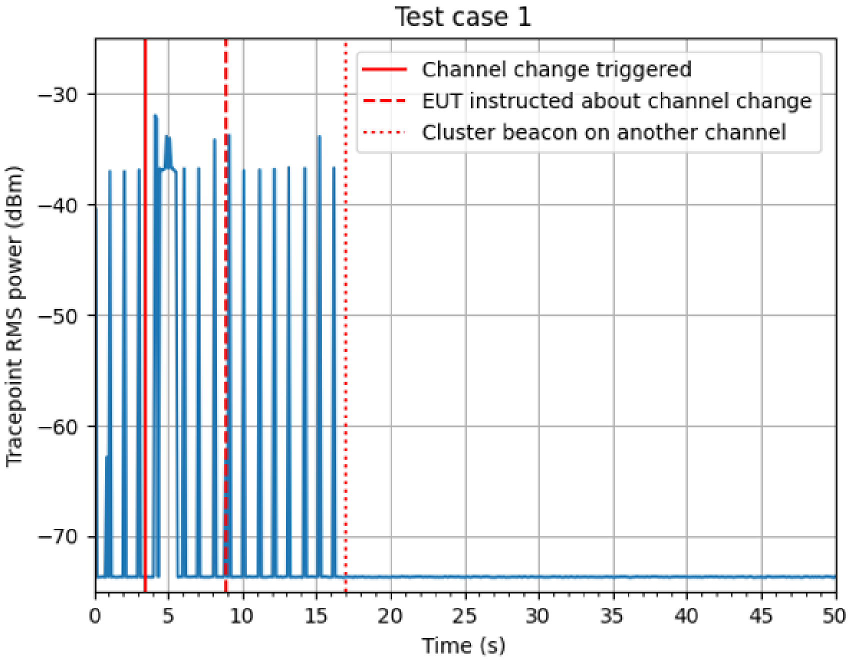


Figure 5.9. *The expected spectrum analyser trace showing the EUT follow the instructions of the companion device.*

Figure 5.9 shows the transmissions of both the EUT and companion device. Due to the low time resolution of the trace, a transmission–response pair for a unicast transmission will occur within a timespan of one trace point, thus they cannot be seen as separate power spikes, but rather as the total sum of the powers within one point. This transmission–response pair was shown in the Figure 5.8.

In this test case instance, the channel change has been triggered after detecting 4 transmissions by the EUT. In Figure 5.9, the time instance at which the channel change is triggered by the tester is shown as the solid red line.

The dashed red line in the Figure 5.9 indicates the time instance at which the companion device transmits the cluster beacon which informs that the next cluster beacon will be on another channel. By zooming in on the Figure 5.9, the cluster beacon transmissions can be seen more clearly as the lower power spikes as shown in the Figure 5.10 below.

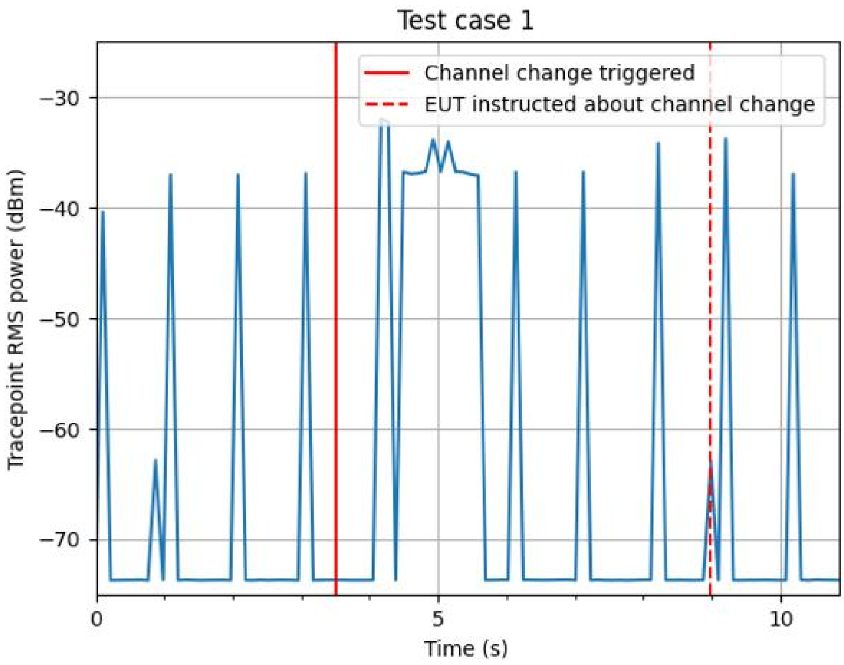


Figure 5.10. *Test case 1 trace showing cluster beacon transmissions of the companion device as the lower power spikes.*

After the instruction received in the cluster beacon, the EUT continues to transmit to the random-access resources on the current channel since the companion device does not change its operating channel until the next occurrence of the cluster beacon[1].

The dotted red line in Figure 5.9 indicates the time instance at which the companion device has changed its operating channel, i.e., transmitted its cluster beacon on a new channel. This should occur after the time defined in the cluster beacon periodicity after the previous beacon.

The time limit for the EUT to cease its transmissions on its current channel is defined as 10 seconds after the first transmission by the EUT after the companion device has changed its operating channel [29]. As seen from the Figure 5.9, the EUT does not transmit anything on the observed channel after the indicated channel change. This results in the time limit not being defined, and the result being 0 seconds, giving a positive test verdict.

---

[1] From the DECT-2020 NR standard point of view, an RD in FT mode is allowed to have its random-access resources on different channel than it is transmitting its cluster beacons. This would allow the companion device to change its operating channel at the same time instance it instructs the EUT.

Test case 2

The acquired spectrum analyser trace for the test case 2 is shown below.

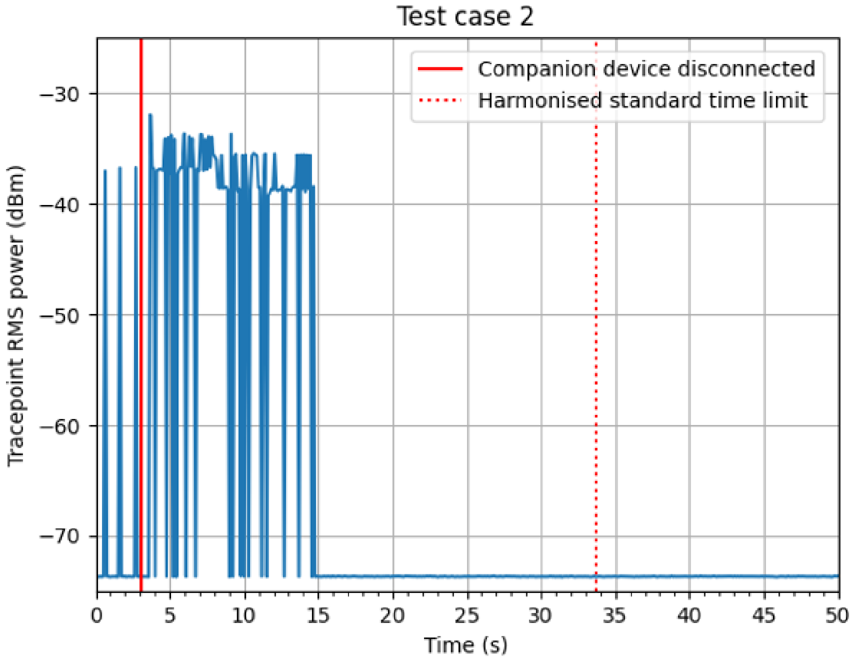


Figure 5.11. *Spectrum analyser trace of EUT transmissions when the companion device is disconnected.*

The Figure 5.11 shows the behaviour of the EUT when the companion device is powered down. After the companion device is powered down (indicated as the solid red line), the EUT transmits a regular transmission but does not get a response in the expected response window. This will cause the EUT to retransmit on the same, previously acquired random access resources unless the resources have expired.

The successful transmissions can be seen as the first 3 power spikes in Figure 5.11, after which the transmission rate significantly increases, depicting the retransmissions in a quick succession. Multiple retransmissions will be done within the timespan of one trace point thus showing an increased RMS level for some trace points.

The transmissions are stopped after the EUT finally considers the connection lost. Among the retransmissions, the EUT may transmit other messages as well, such as configuration request messages when the EUT does not receive an expected cluster beacon [18].

The harmonised standard requires that all transmissions on the used channel should cease within 30 seconds of losing connection with the companion device, where the reference start time is defined to be the end of the 10th transmission of the EUT after losing connection [29].

In Figure 5.11, the trace data indicates that the time between the first transmission, after the companion device is powered down and completely stopping all transmissions, is around 11 seconds. There is no certainty from the traces at which time instance the 10th transmission occurs because of the low time resolution. Therefore, using the first transmission after powering down the companion device as a reference point for the 30-second limit should be a sufficient option for this test implementation since it can only make the requirement tighter. This tightened requirement is indicated in Figure 5.11 as the dotted red line.

The results of both test cases and their relative requirements are summarised in the Table 5.10 below.

Table 5.10. *Results of PT mode tests.*

Test procedure	**Time for EUT to cease its transmissions (s)**	**ETSI EN 301 406-2 Requirement**
Operating channel change	0 s	<10 s
Companion device disconnection	11.1 s	<30 s

Verdict: By acquiring the spectrum analyser traces plotted in Figure 5.8, Figure 5.9 and Figure 5.11, the EUT operating in PT mode can be confirmed to operate according to the random-access requirements of the harmonised standard, by ceasing its operation on a random-access channel within the required time limits.

6. CONFORMANCE TEST DEFINITIONS

In this chapter, a set of new conformance test cases are designed and defined for the DECT-2020 NR MAC layer. At the time of writing this thesis, the specification version is v1.5.1. [18]

6.1 Scope of the test definitions

The MAC layer tests defined for both the FT and PT are done for basic mandatory functionalities that can be observed during any communication between two or more radio devices. The test purposes are derived from the MAC layer specification while taking inspiration from other available standardised conformance test specifications, such as the 3GPP 5G UE conformance specification [21], the standardised ETSI test suites [20] and the Bluetooth GAP test suite [38]. These tests for FT mode include:

- Operating channel and sub-slot selection
- Beaconing transmissions
- Random access procedure
- Association procedure

And for PT mode:

- RD selection
- Association procedure
- Random access transmission
- Random access procedure
- Power control
- Mobility procedure

The test purposes are written with the TPLan notation [23], having a less strict structure and freely used keywords which better fit the conformance requirements of the core specification. The motivation i.e., the purpose of the tested function is briefly described for each defined test purpose. Some procedures that may be tested in a sequence are accompanied by a test sequence chart.

The tester may need to force the IUT to perform specific operations, such as to transmit upper-layer application data to test certain functionalities or indicate to the upper tester that it has received a packet.

In test purposes where the tester is indicated to transmit specific messages to the IUT, those messages should be described in detail within the conformance specification for different profiles. Having the message contents specified makes different test implementations have the same basis and standardises testing.

6.2 MAC layer test definitions for RD in FT mode

This part provides test purposes for MAC layer FT mode functions that are essential for basic interconnectivity between different implementations of DECT-2020 NR.

All the conformance requirements concerning the MAC layer specification refer to ETSI TS 103 636-4 [18] unless otherwise stated.

6.2.1 Initial test states

Due to the autonomous and automatic operation of DECT-2020 NR, the initial states do not require any form of tester or user input to be reached. All connections formed between devices happen automatically when RDs in the same network detect each other.

The initial states for the test purposes (conditionals in the **with** statement) for IUT in FT mode may be divided into these two states:

- Initial state where the IUT in FT mode has not yet selected its operating channel. In other words, the IUT is powered on.
- IUT is beaconing and announcing random access resources.

The beaconing state could be considered as being a stable state that the IUT in FT mode reaches after choosing its operating channel. A stable state does not change without receiving a stimulant. Additionally, the ‘beaconing’ state may be more focused based on whether the IUT has sent a specific message. Having initial states based on a received message is not recommended since it does not always include an observable semantic action from the IUT. The initial state of the test purpose may also include variables and timers.

6.2.2 Operating channel selection

The operating channel selection is an initial operation of an RD operating in FT mode. In this procedure, the RD in FT mode scans channels to find a suitable channel on which it will coordinate local radio resources and transmissions of RDs connecting to it. The conformance requirements for operating channel selection are described in ETSI TS 103 636-4, clause 5.1.2 [18].

For the first test purpose, the RD should pick a short RD ID randomly such that it does not conflict with any other RD in the local area. The task may be more difficult than expected since RDs not beaconing or transmitting periodically may be left undetected and may cause conflicts later.

(1)

```
with {IUT in initial state}
ensure that {
      when {IUT initiates FT mode operation}
      then {IUT selects a unique short RD ID in the local area}
            }
```

DECT-2020 NR supports multiple operating bands [30], and thus the IUT should select the operating channel from within those bands. Additionally, the channel should be selected according to the national regulations.

(2)

```
with {IUT in initial state}
ensure that {
      when {IUT initiates FT mode operation}
      then {IUT selects the operating channel from a supported band}
            }
```

When an RD initiates FT mode operation, it shall conduct a background scan to find a suitable operating channel. The test purpose (3) verifies that when the IUT measures each channel and determines the statuses of their sub-slots, the IUT should select the least occupied channel.

(3)

```
with {IUT in initial state}
ensure that {
      when {IUT has measured all channels during background scan}
      then {IUT selects a channel with the lowest number of ‘busy’ sub-slots
which has the highest number of ‘free’ sub-slots}
            }
```

The core specification allows the IUT to stop the background scan procedure early if a sufficiently good channel is found. The test purpose (4) is designed in a way that is passable even if better channels could be found after stopping the scan.

(4)

```
with {IUT in initial state}
ensure that {
      when {IUT detects a channel with the amount of ‘free’ or ‘possible’ sub-
slots being greater or equal to SCAN_SUITABLE at SCAN_MEAS_DURATION}
      then {IUT selects any channel where the amount of ‘free’ or ‘possible’
sub-slots is greater or equal to SCAN_SUITABLE at SCAN_MEAS_DURATION}
            }
```

The test purpose (5) is to verify that the IUT re-evaluates the channel status periodically at least with the indicated periodicity. By not announcing the ‘busy’ channels in resource announcements, the network should experience fewer collisions even when the listen before talk protocol is used. To verify that the IUT updates the sub-slot statuses, the random-access resources it announces may be monitored.

(5)

```
with {IUT in initial state or beaconing}
ensure that {
      when {IUT selects an operating channel}
      then {IUT regularly updates the statuses of sub-slots defined as ‘free’
or ‘possible’ at least once per timer scanStatusValid}
            }
```

The $DECT\_PROTECTED$ variable brings additional channel selection rules to use [18]. It lowers the periodicity at which the sub-slot statuses should be updated. The method used for determining the statuses is the Last-Minute Scan function.

(6)

```
with {IUT in initial state and DECT_PROTECTED is TRUE}
ensure that {
      when {IUT selects an operating channel}
      then {IUT regularly updates the statuses of sub-slots defined as ‘free’
or ‘possible’ at least once per timer dectProTime}
            }
```

As the used operating channel begins to get more traffic, but most of the occurring transmissions are not targeted towards the IUT, the channel may not anymore be sufficient for the operation of the IUT. The test purpose (7) verifies whether the IUT will begin to search for a better channel to operate on.

(7)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT measures its own channel, and the amount of ‘busy’ sub-slots
is greater or equal to CHANNEL_LOADED at SCAN_MEAS_START}
      then {IUT re-initiates channel selection procedure}
            }
```

6.2.3 Beaconing transmissions

The conformance requirements for the beaconing transmissions are defined in ETSI TS 103 636-4, clause 5.1.5, and for the network and cluster beacon messages in clauses 6.4.2.2 and 6.4.2.3 respectively [18].

Since the network beacons can be transmitted on a limited set of channels, signalling the operating channel and timing information of a device in FT mode, significantly speeds up the process of setting up a connection and initialising data transfer [18].

The test purpose (1) verifies that the timing and channel information of the cluster beacon transmission is correctly indicated in the network beacon message.

(1)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT sends a “Network beacon message” containing “Time to next” and
“Next Cluster Channel”}
      then {IUT sends a “Cluster beacon message” after “Time to next” to “Next
Cluster Channel”}
            }
```

The variables “time to next” and “next cluster channel” indicate the time until the next occurrence of the cluster beacon message in microseconds, and the centre frequency is indicated as the absolute channel frequency number defined in ETSI TS 103 636-2 [30]. The transmission timing follows an accuracy requirement of $\pm 10\ \mathrm{ppm}$ [30].

The test purposes (2) and (3) verify that the RD in FT mode begins transmitting network and cluster beacons with regular periodicity after the selection of the operating channel. As an example, having accurately timed beacons allows low-powered devices to only wake up briefly to listen to the beacon by knowing the exact timing.

(2)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT sends a “Network beacon message”}
      then {IUT sends another “Network beacon message” after the time indicated
in “Network beacon period”}
            }
```

(3)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT sends a “Cluster beacon message”}
      then {IUT sends another “Cluster beacon message” after the time indicated
in “Cluster beacon period”}
            }
```

Note: When implementing the periodicity test, multiple consecutive periodic transmissions should be monitored to verify conformance.

To ease the implementation of a test suite, a test procedure chart may be added for each feature to clarify testing and to help identify how different test purposes are related.

Table 6.1. *Test sequence for test purposes defined for beaconing transmissions.*

St	Procedure	Message Sequence		TP	Verdict
		IUT-TST	Message		
1	IUT transmits a network beacon message indicating “Time to next” and “Next Cluster channel” in Network Beacon IE.	-->	Network beacon message	-	-
2	Check: Does the IUT transmit a network beacon message after the time indicated in “Network beacon period” after step 1?	-->	Network beacon message	2	P
3	Check: Does the IUT transmit a cluster beacon message after the time indicated in “Time to next” on the channel indicated in “Next Cluster channel”? (Note 1)	-->	Cluster beacon message	1	P
4	Check: Does the IUT transmit a cluster beacon message after the time indicated in “Cluster beacon period” after step 3?	-->	Cluster beacon message	3	P
Note 1: The IUT may transmit multiple Network beacon messages before transmitting a Cluster beacon message. Note 2: The transmission timing of the beacons shall follow the accuracy requirement defined in ETSI TS 103 636-2 [30].					

6.2.4 Random-Access procedure

The conformance requirements for the random-access procedure are defined in ETSI TS 103 636-4 clause 5.3, and clause 6.4.3.4 for the Random-Access Resource IE [18].

The initial beaconing state for these tests is automatically reached after the RD in FT mode has selected an operating channel and can be confirmed by observing beaconing transmissions.

The test purposes verify that the EUT in FT mode is listening for transmissions on the random-access resources it has announced and is able to send HARQ feedback when requested or behave logically according to the received messages.

When the EUT receives a packet, it must be able to decode and correctly receive the PCC to be able to decode the PDC. This is because the PCC contains the PHY control field used to indicate the packet size and MCS required for decoding the PDC [18] [37]. Thus, if the PDC is indicated to fail, it means that the PCC has been successfully received. If the PCC is indicated to fail, it means that the receiver has failed to decode the PCC trying both 40- and 80-bit header lengths.

The test purpose (1) combines the PCC-failure of all header types and formats, since it is not able to acquire the information related to those.

(1)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT receives any transmission and PCC decoding fails}
      then {IUT ignores the packet}
            }
```

Test purposes (2) and (3) test whether the RD in FT mode transmits a random-access response to a transmission requesting HARQ-feedback when the result of decoding the packet either succeeds or fails.

(2)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT receives a transmission containing “PHY header type 2” indi-
cating “format 000”, and PDC decoding fails}
      then {IUT sends a response message containing “HARQ-feedback” indicating
NACK within the RACH response window}
            }
```

(3)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT successfully receives a transmission containing “PHY header
type 2” indicating “format 000”}
      then {IUT sends a response message containing “HARQ-feedback” indicating
ACK within the RACH response window}
            }
```

If the IUT receives a packet that does not request HARQ feedback, upon failing to decode the PDC data, the IUT ignores the data part. It is expressed in test purpose (4).

(4)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT receives a transmission containing “PHY header type 2” indi-
cating “format 001”, and PDC decoding fails}
      then {IUT ignores the PDC data}
            }
```

The test purpose (5) verifies whether the IUT behaves according to the received MAC PDU. To clarify, the transmitter using the header format 001 does not require nor expect HARQ feedback, but when required to behave logically, a response may be required. This test purpose is untestable on its own due to ambiguity. Test purposes for the individual functionalities are defined in their own sections.

(5)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT successfully receives a transmission containing “PHY header
type 2” indicating “format 001”}
      then {IUT behaves according to the received MAC PDU}
            }
```

Note: if the received MAC PDU indicates a control message requiring a logical response, such as an association request, the EUT shall respond inside the RACH response window.

The random-access procedure test purposes, except (5), can be included as a single test sequence, as shown in the table below.

Table 6.2. *FT mode random-access procedure test sequence.*

St	Procedure	Message Sequence		TP	Verdict
		IUT-TST	Message		
1	TESTER sends an undecodable packet to IUT.	<--	-	-	-
2	Check: Does the IUT ignore the received packet?	-	-	1	P
3	TESTER sends a packet with faulty PDC to IUT with header type 2, format 000.	<--	MAC PDU	-	-
4	Check: Does the IUT send a response message containing HARQ feedback indicating NACK?	-->	HARQ feedback	2	P
5	TESTER sends a valid packet to IUT with header type 2, format 000.	<--	MAC PDU	-	-
6	Check: Does the IUT send a response message containing HARQ feedback indicating ACK?	-->	HARQ feedback	3	P
7	TESTER sends a packet with faulty PDC to IUT with header type 2 format 001.	<--	MAC PDU	-	-
8	Check: Does IUT ignore the received packet?	-	-	4	P

6.2.5 Association procedure

The conformance requirements for the association procedure are defined in ETSI TS 103 636-4, clause 5.8, and for the MAC messages in clauses 6.4.2.(4 – 6) [18].

The test purpose (1) checks if the EUT responds to the received message accordingly only having a requirement to respond. In any situation, there should be a logical response, whether the response indicates acceptance or rejection. It is up to the implementation to decide whether it can accept or reject the request. After the transmission of the response, the IUT should assume the association either as successful or unsuccessful according to the content.

(1)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT receives an “Association request message”}
      then {IUT sends an “Association response message” within the RACH re-
sponse window}
            }
```

The test purposes (2) and (3) define a partially untestable test for verifying the association release, since there is no specified mandatory semantic action occurring from releasing an association.

(2)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT sends an "Association release message"}
      then {IUT considers association with the target released}
            }
```

(3)

```
with {IUT beaconing and announcing RACH resources}
ensure that {
      when {IUT receives an "Association release message"}
      then {IUT considers association with the sender released}
            }
```

6.3 MAC layer test definitions for RD in PT mode

This part provides test purposes for MAC layer PT mode functions that are used for basic interconnectivity between implementations of DECT-2020 NR.

All the conformance requirements concerning the MAC layer specification refer to ETSI TS 103 636-4 [18] unless otherwise stated.

6.3.1 Initial test states

The initial states for the IUT in PT mode may be divided into two groups, ones where the IUT is associated with an RD in FT mode and ones where not, i.e., connected, and unconnected, or having a route to the sink or not. These states can further be focused based on whether the RD has transmitted specific messages.

- Un-associated / unconnected / initial state
- Associated / connected

The connected state includes the assumption that the IUT is periodically receiving the cluster beacon messages and the indication of random-access resources.

6.3.2 RD selection for association

The conformance requirements for the association procedure are defined in ETSI TS 103 636-4, clause 5.8 [18]. The used messages, association request, response, and release are defined in clauses 6.4.2.4, 6.4.2.5, and 6.4.2.6 respectively [18].

The test purpose (1) checks whether the RD tries to associate with an RD in the desired network. The rest of the test purposes (2) and (3) verify that the selection of the target RD is done optimally as described in the specification [18].

(1)

```
with {IUT in unconnected state}
ensure that {
      when {IUT receives “Network beacon messages” from multiple RDs}
      then {IUT may initiate reception of “Cluster beacon messages” indicating
desired network ID}
            }
```

(2)

```
with {IUT in unconnected state}
ensure that {
      when {IUT receives “Cluster beacon messages” from multiple RDs exceeding
the minimum RSSI-2 quality level}
      then {IUT initiates the association procedure with the RD providing the
lowest route cost}
            }
```

(3)

```
with {IUT in unconnected state}
ensure that {
      when {IUT receives “Cluster beacon messages” from multiple RDs exceeding
the minimum RSSI-2 quality level and indicating identical lowest route costs}
      then {IUT initiates association procedure with an RD providing the high-
est RSSI-2 value}
            }
```

6.3.3 Association procedure

The association procedure tests verify that the IUT in PT mode is able to automatically perform the association procedure with an RD in FT mode when wanting to join a network. The conformance requirements for the association procedure are as defined in FT mode tests.

The test purpose (1) verifies whether the IUT will transmit an association request to an RD which it considers the best option. This test does not consider which RD the IUT chooses.

(1)

```
with {IUT in unconnected state}
ensure that {
      when {IUT has selected a target RD for association}
      then {IUT sends an “Association request message” to the target RD}
            }
```

The test purpose (2) is a message-specific random-access procedure test for association procedures.

(2)

```
with {IUT having sent an “Association request message” to an RD in FT mode}
ensure that {
      when {IUT does not receive an “Association response message” within the
RACH response window}
      then {IUT initiates a new random-access procedure for sending the “Asso-
ciation request message”}
            }
```

The test purposes (3) and (4) verify the operation of the IUT when it receives an association response message indicating accepted association.

(3)

```
with {IUT having sent an “Association request message” to an RD in FT mode}
ensure that {
      when {IUT receives an “Association response message” indicating associ-
ation accepted}
      then {IUT considers association successful if it can use the configura-
tion for communication}
            }
```

For the test purpose (4), the IUT is unable to use the signalled configuration and thus an association release is required to be transmitted since the RD in FT mode would otherwise consider the association successful.

(4)

```
with {IUT having sent an “Association request message” to RD in FT mode}
ensure that {
      when {IUT receives an “Association response message” indicating associ-
ation accepted and indicating a configuration it is unable to use}
      then {IUT sends an “Association release message” indicating “Incompatible
configuration”}
            }
```

When the association request of the IUT has been rejected, it should retry the association procedure, while also following the reject timers.

(5)

```
with {IUT having sent an “Association request message” to RD in FT mode}
ensure that {
      when {IUT receives “Association response message” indicating association
rejected}
      then {IUT does not send a new “Association request message” to the same
RD until timer rejectTimer expires}
            }
```

All RDs should consider their association with another RD released when receiving or transmitting an association release message without further questioning. The association release message may be transmitted at any time, after which the IUT may then freely re-initiate the RD selection procedure.

(6)

```
with {IUT in connected state}
ensure that {
      when {IUT receives an “Association release message”}
      then {IUT considers association with the sender released}
            }
```

(7)

```
with {IUT in connected state}
ensure that {
      when {IUT sends an “Association release message”}
      then {IUT considers association with the target released}
            }
```

6.3.4 Random-Access transmission

The random-access tests for the PT mode verify that the IUT is capable of transmitting and retransmitting to the random-access resources announced in a cluster beacon message by the tester in FT mode. The conformance requirements for random access transmission are defined in ETSI TS 104 636-4, clause 5.3.3 [18].

The test purposes (1) and (2) test the LBT mechanism used to access the channel, and the initial random-access transmission capability for both busy and free channels.

(1)

```
with {IUT in connected state}
ensure that {
      when {IUT has a MAC PDU to be transmitted and the channel is ‘free’}
      then {IUT performs LBT and transmits to the RACH resources}
            }
```

(2)

```
with {IUT in connected state}
ensure that {
      when {IUT has a MAC PDU to be transmitted and the channel is ‘busy’}
      then {IUT performs LBT and defers from transmitting}
            }
```

The following test purposes (3), (4), and (5) verify that the IUT listens for a random-access response after transmitting to the random-access resources and behaves according to the response. The IUT can only receive the response if the has been able to decode the control information.

(3)

```
with {IUT having sent a unicast data packet containing “PHY header type 2“
indicating “format 000” to RD in FT mode}
ensure that {
      when {IUT does not receive a response message as PHY control in the RACH
response window}
      then {IUT initiates a new random-access procedure}
            }
```

(4)

```
with {IUT having sent a unicast data packet containing “PHY header type 2”
indicating “format 000” to RD in FT mode}
ensure that {
      when {IUT receives a response message as PHY control indicating NACK}
      then {IUT initiates a new random-access transmission}
            }
```

(5)

```
with {IUT having sent a unicast data packet containing “PHY header type 2”
indicating “format 000” to RD in FT mode}
ensure that {
      when {IUT receives a response message as PHY control indicating ACK}
      then {IUT considers the transmission successful}
            }
```

For the test purposes (3), (4), and (5), the response may be either a unicast message or a broadcast message including a broadcast indication IE [18].

The test purposes (3), (4), and (5) should be tested with different random-access resource IE configurations. These should include:

- Channel field present: Random access transmission should occur on the indicated channel.
- Channel 2 field present: Random-access response should be received when it is transmitted on the indicated channel.

The test purpose (6) tests whether the IUT is able to consider previously acquired random access resources invalid in the case of losing connection to the RD in FT mode.

(6)

```
with {IUT having sent a unicast data packet containing "PHY header type 2"
indicating "format 000" to RD in FT mode}
ensure that {
      when {IUT does not receive a response message within the RACH response
window}
      then {IUT initiates a new random-access procedure and starts timer
dectRachResourceFailure}
      when {IUT does not receive a response message or "Cluster beacon message"
containing "Random-access resource IE" before timer dectRachResourceFailure
expires}
      then {IUT considers resources invalid and releases association with the
RD in FT mode}
            }
```

Test purpose (7) verifies whether the transmitted packet length is less or equal to the maximum allowed RACH length. The maximum allowed packet length is instructed in the random-access resource IE.

(7)

```
with {IUT in connected state}
ensure that {
      when {IUT has a MAC PDU to be transmitted}
      then {IUT transmits the packet if it fits on the RACH resources}
            }
```

6.3.5 Power control

The conformance requirements for power control are defined in ETSI TS 103 636-4, clause 5.1.5 [18].

The power control test purposes (1) and (2) verify that the IUT in PT mode does not exceed the power level constraints set by the coordinating RD in FT mode. The used power levels by the IUT may be identified from the PHY control field, or by measuring the actual transmission power using a spectrum analyser.

(1)

```
with {IUT in unconnected or connected state}
ensure that {
      when {IUT receives a beacon message}
      then {IUT adjusts its power level to equal or less than the transmit
power indicated in the PHY control field of the beacon message, before initi-
ating any transmission towards the RD in FT mode}
            }
```

(2)

```
with {IUT in unconnected or connected state}
ensure that {
      when {IUT receives a beacon message indicating the presence of clusters
max TX power field in network/cluster beacon message IE}
      then {IUT adjusts its power level to equal or less than instructed in
the clusters max TX power field before initiating any transmission towards the
RD in FT mode}
            }
```

The test purpose (3) tests how the IUT adapts its transmission power to the channel quality. For it to be testable, a tester needs to inform the IUT about the channel quality using the Channel Quality Indicator (CQI) included in feedback messages. The CQI informs the IUT about the MCS the tester is able to receive without exceeding 10% BLER [18]. For the test purposes, the tester should indicate the highest possible MCS satisfying the BLER criteria, even if does not support the indicated MCS.

The method to verify whether the minimum power has been chosen by the IUT is simple. The IUT should select the MCS informed in the CQI with the used power level or adjust the power level to match the used MCS with the MCS indicated in the CQI. If the MCS informed in the CQI is higher than the used MCS, the transmission power should be lowered or increased if the CQI indicates a lower MCS.

(3)

```
with {IUT in unconnected or connected state}
ensure that {
      when {IUT transmits a unicast message}
      then {IUT adjusts its power level as a minimum to reach the target BLER
with the used MCS}
            }
```

A test sequence chart for the power control tests is proposed below in Table 6.3.

Table 6.3. *PT mode power control test sequence.*

St	Procedure	Message Sequence		TP	Verdict
		IUT-TST	Message		
1	TESTER transmits a cluster beacon without indicating TX power field.	<--	Cluster Beacon message	-	-
2	Check: Does the IUT transmit unicast messages with a power level equal to or lower than the cluster beacon was transmitted with?	-->	MAC PDU	1	P
3	TESTER transmits a cluster beacon indicating TX power field and Clusters Max TX power.	<--	Cluster Beacon message	-	-
4	Check: Does the IUT transmit unicast messages with a power level equal to or lower than instructed in the Clusters Max TX Power field?	-->	MAC PDU	2	P
5	Check: Does the IUT adjust its transmission power such that the MCS indicated in the CQI matches the used MCS?	-->	MAC PDU	3	P

6.3.6 Mobility procedure

The conformance requirements for the mobility procedures are defined in ETSI TS 103 636-4, clause 5.7 [18]. The mobility procedure is initiated by an RD in PT mode, and it includes measuring RSSI-2 values of received beacon transmissions.

The purpose of the test is to ensure that when connections between associated RDs vary in signal quality, the radio devices are able to detect this and begin searching for better options in terms of link quality. The link quality is based on RSSI-2 measurement, which is the power measured from a received packet from which the control information (PCC) can be decoded. In the case of DECT, the RSSI-2 can be measured from the suitable cluster and network beacon messages. Variations in signal quality occur mostly due to the movement of radio devices in comparison to one another, thus being called the mobility procedure.

The benefit and importance of the mobility procedure is to keep the DECT-2020 NR mesh network optimised and heal the network in the case of router failures. Poor link qualities may increase the load of a network due to retransmissions, and thus lower the actual data throughput.

(1)

```
with {IUT in connected state}
ensure that {
      when {IUT receives beacon messages of other RD indicating better link
quality of RELATIVE_QUALITY countToTrigger times in a row}
      then {IUT initiates association procedure towards the RD providing the
better route and releases the current association}
            }
```

Note: The association may be released either before or after the new association.

7. TEST SETUP EXAMPLES

This chapter demonstrates two possible types of test systems for implementing conformance test cases and verifying results. Testing using simulations and physical test setups.

7.1 Testing architecture

Conformance testing of a single protocol layer always includes a tester and the system under testing (SUT). How the testing is performed in practice is a test implementation question. Commonly, the IUT needs to be tested as a part of a larger system, where the tested functionality is embedded. A general test architecture for embedded testing is shown in Figure 7.1.

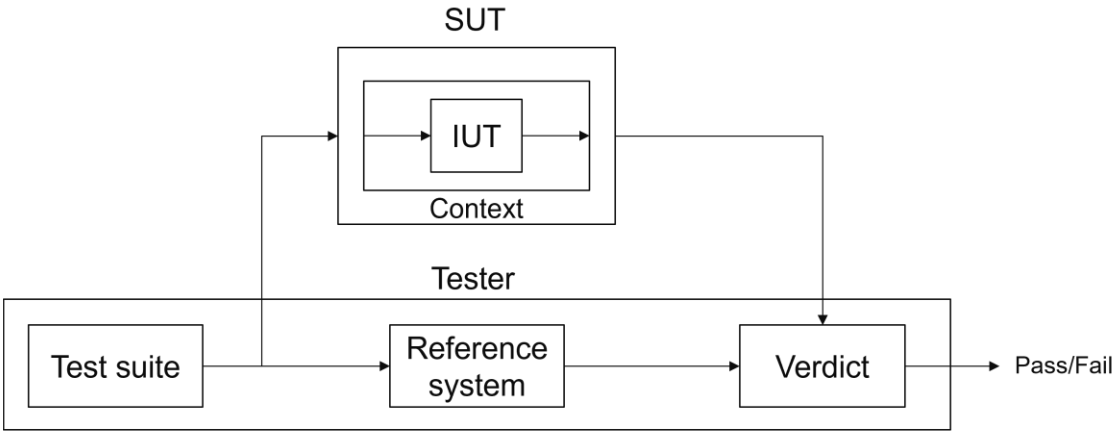


Figure 7.1. *General test architecture for embedded IUT testing, where the tester compares the outputs of a reference system with the ones of the SUT to define a verdict [39].*

In embedded testing, The IUT can only be accessed by tester through other intermediate functionality of the system, called context, as shown in Figure 7.1. The tester thus needs to decide the verdicts based on the behaviour of the whole system. This requires that the functionality of the surrounding context should be known and assumed to be correctly implemented [39].

In some test suites such as in the Bluetooth general access profile test suite, the system under testing takes input and gives output to two different testers, called lower tester and an upper tester [38].

7.1.1 Upper and lower testers

A protocol specification defines the behaviour of a protocol entity at the upper and lower access points, i.e., service access points (SAP). The SAPs that are accessible for a tester to observe and control the IUT are called Points of Control and Observation (PCO). For protocol conformance testing, two PCOs are used, one for accessing the IUT from the lower PCO and one for the upper PCO, resulting in the use of a lower and upper tester.

The role of the upper tester is to control and observe the IUT from the upper PCO. This could be considered as accessing the IUT via the application interface. The upper tester can thus control and observe the IUT within the limitations of the implementation. For example, the upper tester may configure the IUT to operate in a certain mode, such as forcing the RD to operate in FT or PT-only modes or make the IUT transmit or receive application data.

A lower tester observes and controls the IUT via the lower PCO. This can be considered as the physical layer access point of the IUT, i.e., observing and controlling the IUT using physical signals. A lower tester may operate as another RD sending standard compliant messages to the IUT, such that the IUT responds as it would in a real-use scenario. The lower tester may modify the message contents artificially to test the behaviour of different functions, and even modify them to be invalid or undecodable in order to observe the IUT behaviour in those cases. The lower tester observes the behaviour of the IUT by capturing its transmissions. In some cases, such as testing the RD selection procedure of DECT-2020 NR, multiple lower testers may be needed, or the lower tester needs to simulate the whole network.

The tester entity coordinates both the lower and upper testers to execute the tests and to define verdicts according to a standardised test suite, as shown in Figure 7.1.

7.1.2 Test architecture for DECT-2020 NR

In this thesis, the implementation under testing is the MAC layer implementation of the DECT-2020 NR profile for the Wirepas 5G mesh.

A possible test architecture for a DECT-2020 NR MAC layer implementation is shown below in Figure 7.2. It is based on general test architecture for embedded testing, where the IUT is a part of a larger system (SUT) [39]. The upper tester (UT) accesses the SUT through the application interface, and the lower tester (LT) from the PHY layer. In Figure 7.2, the MAC protocol is the target for testing, indicated as IUT.

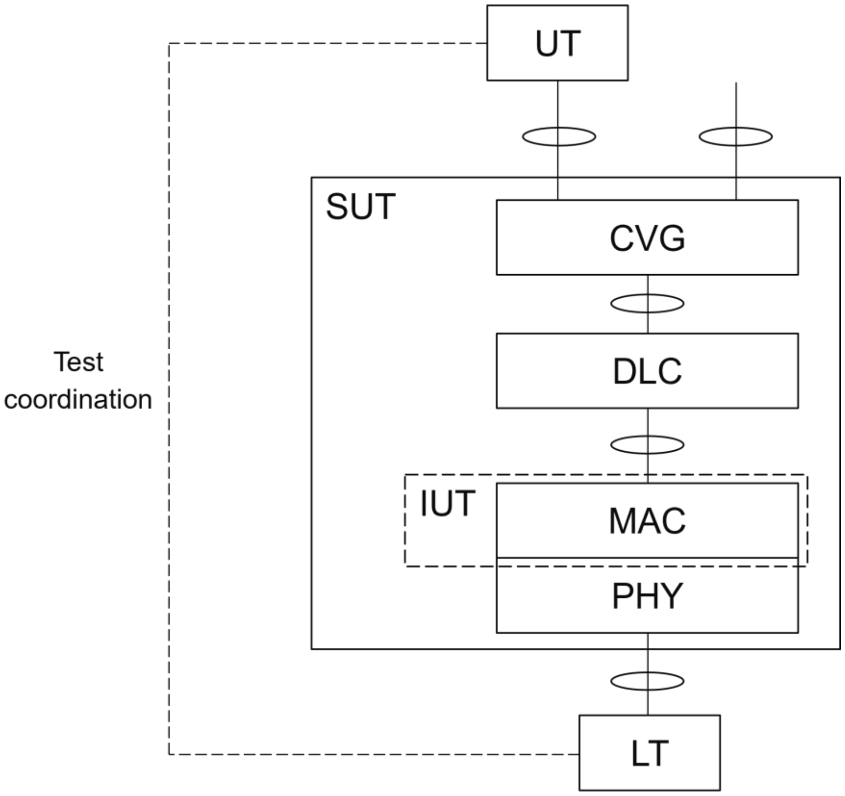


Figure 7.2. Test architecture for DECT-2020 NR embedded testing, where the MAC protocol is the IUT. Includes both the upper and lower testers (UT & LT).

The lower and upper testers are parts of the tester, where they can either control or observe the IUT through the context via the Points of Control and Observation (PCO). Naturally, observing the behaviour is used for defining any verdicts.

7.2 Protocol conformance testing using Wireshark

Wireshark [40] is a network protocol analyser tool which allows inspection of sent and received messages on a bit level. Wireshark allows the parsing of captured packets to create an easily inspectable tree structure from the information elements, headers and bitfields.

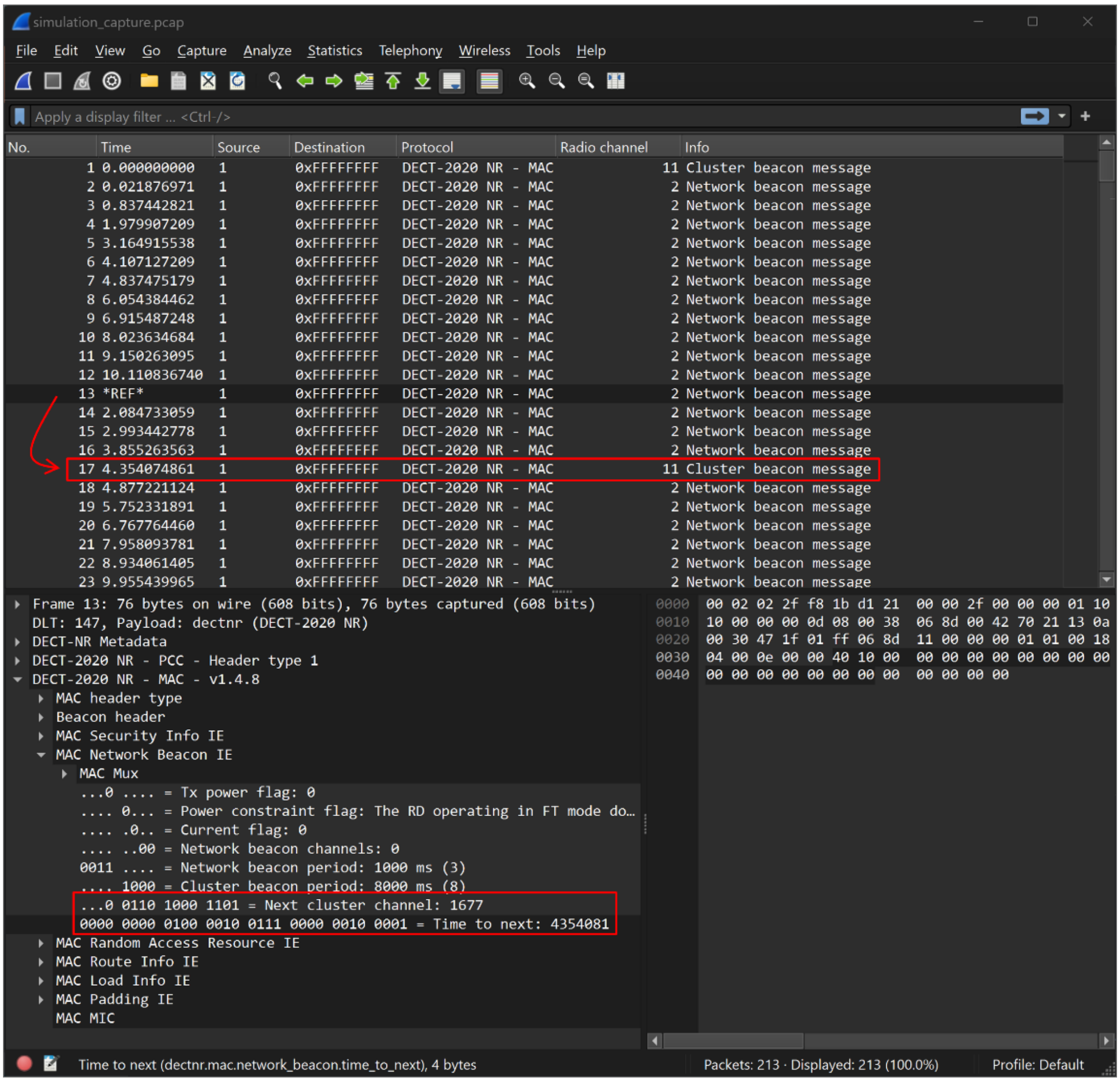
The testing is done by inspecting a packet capture acquired from a system simulation where the simulated RDs use the implementation under testing (IUT). From the test architecture point of view, the system simulation includes the IUT, the upper tester in the form of the simulation application, and the control part of the lower tester which simulates the other nodes in the network. The packet captures along with the Wireshark operate as the observing part of the lower tester.

To be able to inspect the captured packet contents, the simulator does not cipher the MAC PDUs. The captured packets are parsed using a custom-made DECT-2020 NR

Wireshark plugin. Wireshark does not directly test anything, but the contents of the packets, their sequences, and timing information may be used to manually check the behaviour of the implementation against the test purposes defined in a test specification.

7.2.1 Beaconing transmissions; Cluster beacon timing

For inspecting the beaconing functionalities, a simulation where a single RD is operating in FT mode is ran. The test purpose (1) defined for beaconing transmissions in paragraph 6.2.3 may be tested using the following method as shown in Figure 7.3 below.



```
No.       Time          Source  Destination  Protocol            Radio channel  Info
        1 0.000000000   1       0xFFFFFFFF   DECT-2020 NR - MAC            11 Cluster beacon message
        2 0.021876971   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        3 0.837442821   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        4 1.979907209   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        5 3.164915538   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        6 4.107127209   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        7 4.837475179   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        8 6.054384462   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
        9 6.915487248   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       10 8.023634684   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       11 9.150263095   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       12 10.110836740  1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       13 *REF*         1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       14 2.084733059   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       15 2.993442778   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       16 3.855263563   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       17 4.354074861   1       0xFFFFFFFF   DECT-2020 NR - MAC            11 Cluster beacon message
       18 4.877221124   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       19 5.752331891   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       20 6.767764460   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       21 7.958093781   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       22 8.934061405   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
       23 9.955439965   1       0xFFFFFFFF   DECT-2020 NR - MAC             2 Network beacon message
```

```
Frame 13: 76 bytes on wire (608 bits), 76 bytes captured (608 bits)
DLT: 147, Payload: dectnr (DECT-2020 NR)
DECT-NR Metadata
DECT-2020 NR - PCC - Header type 1
DECT-2020 NR - MAC - v1.4.8
  MAC header type
  Beacon header
  MAC Security Info IE
  MAC Network Beacon IE
    MAC Mux
    ...0 .... = Tx power flag: 0
    .... 0... = Power constraint flag: The RD operating in FT mode do…
    .... .0.. = Current flag: 0
    .... ..00 = Network beacon channels: 0
    0011 .... = Network beacon period: 1000 ms (3)
    .... 1000 = Cluster beacon period: 8000 ms (8)
    ...0 0110 1000 1101 = Next cluster channel: 1677
    0000 0000 0100 0010 0111 0000 0010 0001 = Time to next: 4354081
  MAC Random Access Resource IE
  MAC Route Info IE
  MAC Load Info IE
  MAC Padding IE
  MAC MIC
```

```
0000  00 02 02 2f f8 1b d1 21  00 00 2f 00 00 00 01 10
0010  10 00 00 00 0d 08 00 38  06 8d 00 42 70 21 13 0a
0020  00 30 47 1f 01 ff 06 8d  11 00 00 00 01 01 00 18
0030  04 00 0e 00 00 40 10 00  00 00 00 00 00 00 00 00
0040  00 00 00 00 00 00 00 00  00 00 00 00
```

Time to next (dectnr.mac.network_beacon.time_to_next), 4 bytes

Packets: 213 · Displayed: 213 (100.0%)

Profile: Default

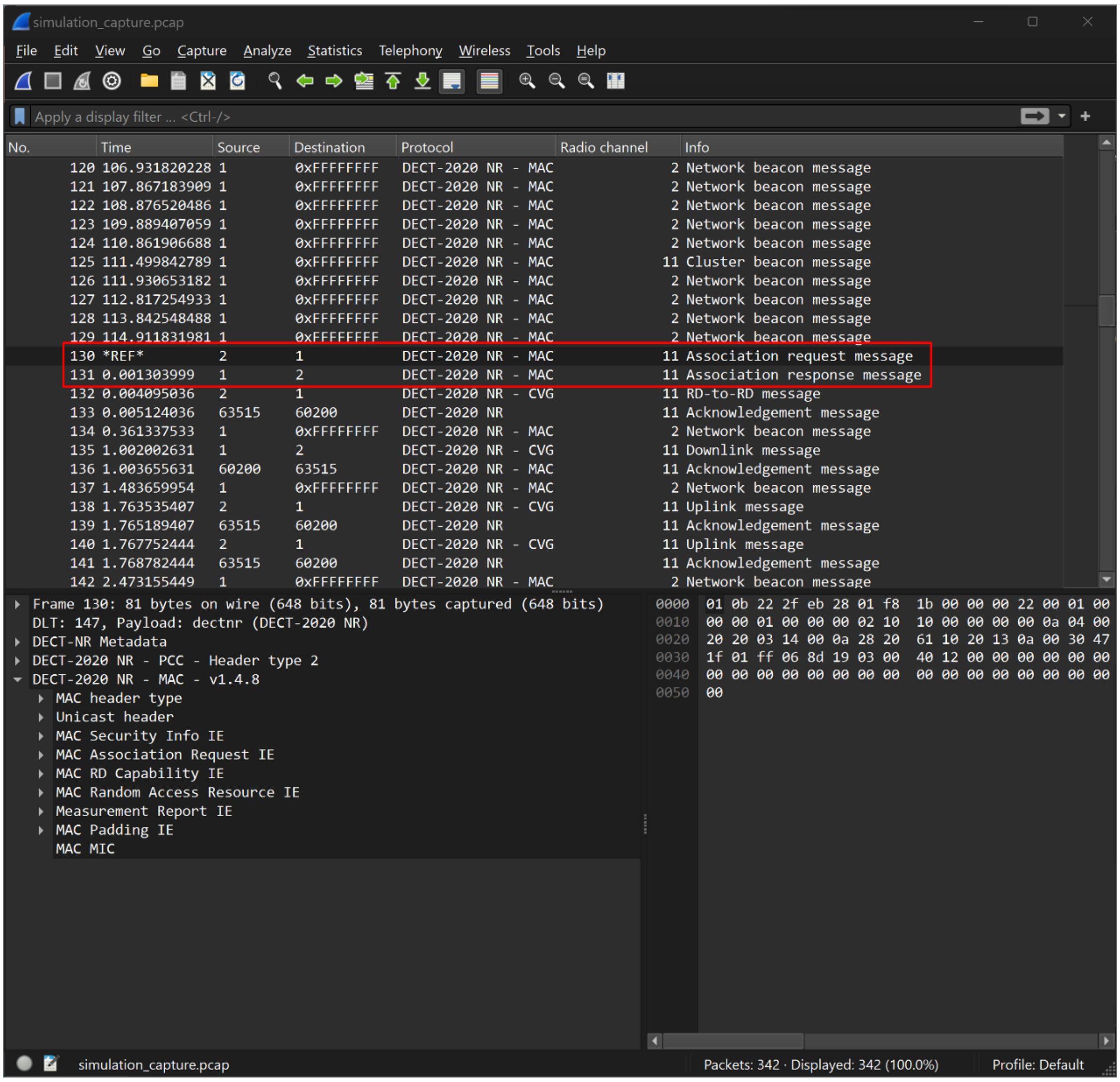
Figure 7.3. *Inspection of Cluster beacon timing and channel information provided in a Network beacon.*

In Figure 7.3, the information about the cluster beacon timing and channel can be seen from a Network beacon IE included in any Network beacon message. The “Next cluster channel” field indicates the used channel frequency for the next cluster beacon with 13 bits as an absolute channel frequency number [30]. The timing is indicated in the “Time to next” field in microseconds as a 32-bit value.

As in the example seen in Figure 7.3, by setting the timing of the inspected network beacon message as a time reference, the cluster beacon message can be seen transmitted after $4\,354\,074\,\mu\mathrm{s}$. The time indicated in the network beacon message is $4\,354\,081\,\mu\mathrm{s}$, thus showing $7\,\mu\mathrm{s}$ error, but which is in the allowed timing accuracy of $\pm 10\ \mathrm{ppm}$ ($\pm 43.5\ \mu\mathrm{s}$) [30]. The Figure 7.3 also shows that the cluster beacon message is transmitted on the indicated radio channel (1677 being the 11th radio channel for DECT-2020 NR in band 1).

7.2.2 Association procedure; Association response

The association procedure is an initial message exchange procedure that two RDs perform to set up unicast data exchange. Since both RDs have the same implementation, both the FT and PT mode behaviour could be checked using the same packet capture. In the simulation of two RDs, the IUT in FT mode has ID 1, while the IUT in PT mode has ID 2.



```
No.     Time           Source   Destination  Protocol             Radio channel  Info
    120 106.931820228 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    121 107.867183909 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    122 108.876520486 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    123 109.889407059 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    124 110.861906688 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    125 111.499842789 1        0xFFFFFFFF   DECT-2020 NR - MAC             11 Cluster beacon message
    126 111.930653182 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    127 112.817254933 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    128 113.842548488 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    129 114.911831981 1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    130 *REF*         2        1            DECT-2020 NR - MAC             11 Association request message
    131 0.001303999   1        2            DECT-2020 NR - MAC             11 Association response message
    132 0.004095036   2        1            DECT-2020 NR - CVG             11 RD-to-RD message
    133 0.005124036   63515    60200        DECT-2020 NR                   11 Acknowledgement message
    134 0.361337533   1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    135 1.002002631   1        2            DECT-2020 NR - CVG             11 Downlink message
    136 1.003655631   60200    63515        DECT-2020 NR - MAC             11 Acknowledgement message
    137 1.483659954   1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
    138 1.763535407   2        1            DECT-2020 NR - CVG             11 Uplink message
    139 1.765189407   63515    60200        DECT-2020 NR                   11 Acknowledgement message
    140 1.767752444   2        1            DECT-2020 NR - CVG             11 Uplink message
    141 1.768782444   63515    60200        DECT-2020 NR                   11 Acknowledgement message
    142 2.473155449   1        0xFFFFFFFF   DECT-2020 NR - MAC              2 Network beacon message
```

```
▸ Frame 130: 81 bytes on wire (648 bits), 81 bytes captured (648 bits)
  DLT: 147, Payload: dectnr (DECT-2020 NR)
▸ DECT-NR Metadata
▸ DECT-2020 NR - PCC - Header type 2
▾ DECT-2020 NR - MAC - v1.4.8
   ▸ MAC header type
   ▸ Unicast header
   ▸ MAC Security Info IE
   ▸ MAC Association Request IE
   ▸ MAC RD Capability IE
   ▸ MAC Random Access Resource IE
   ▸ Measurement Report IE
   ▸ MAC Padding IE
     MAC MIC
```

```
0000  01 0b 22 2f eb 28 01 f8  1b 00 00 00 22 00 01 00
0010  00 00 01 00 00 00 02 10  10 00 00 00 00 0a 04 00
0020  20 20 03 14 00 0a 28 20  61 10 20 13 0a 00 30 47
0030  1f 01 ff 06 8d 19 03 00  40 12 00 00 00 00 00 00
0040  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
0050  00
```

Figure 7.4. *Inspection of association procedure between two simulated RDs.*

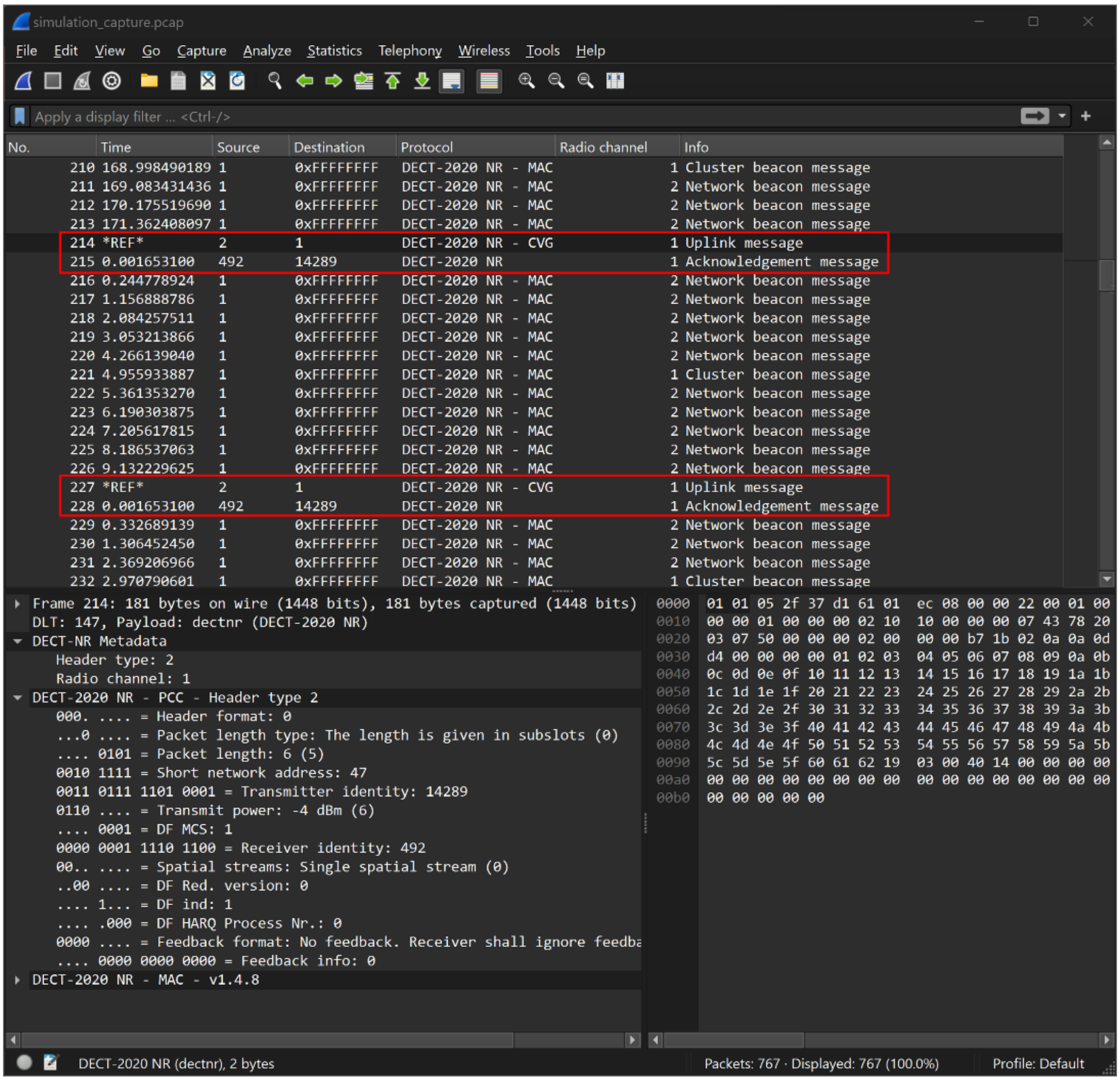
In Figure 7.4, the IUT in PT mode can be seen to initiate the association procedure automatically towards the IUT in FT mode by sending an association request. The IUT in FT mode receives the request and transmits a response message as required, fulfilling a test purpose defined in an earlier chapter. The packet capture can be used for thorough checking of the requirements such as:

- Static requirements: Having the mandatory headers and IEs in both request and response messages.
- Dynamic timing requirements: Transmitting the response in the response window according to the signalled configuration.
- Dynamic requirements: Following transmissions are transmitted according to the capabilities of the RDs, etc.

Defining a verdict for a single test purpose in the test specification may require checking the contents of multiple different messages, since the requirements commonly depend on the signalled configurations, especially for tests focusing on the operation of an RD in PT mode.

7.2.3 Random access procedures; Random access response

After a successful association, the IUT in PT mode is configured to transmit uplink data packets to the IUT in FT mode once every 10 seconds once it has acquired a route to the sink, i.e., associated with an RD in FT mode. The data is transmitted with the header format 000 which requires HARQ feedback from the receiver. Figure 7.5 below shows a couple of unicast transmission occurrences titled as “uplink message”.



```
No.    Time           Source  Destination  Protocol              Radio channel  Info
   210 168.998490189 1        0xFFFFFFFF   DECT-2020 NR - MAC                 1 Cluster beacon message
   211 169.083431436 1        0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   212 170.175519690 1        0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   213 171.362408097 1        0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   214 *REF*          2       1            DECT-2020 NR - CVG                 1 Uplink message
   215 0.001653100    492     14289        DECT-2020 NR                       1 Acknowledgement message
   216 0.244778924    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   217 1.156888786    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   218 2.084257511    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   219 3.053213866    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   220 4.266139040    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   221 4.955933887    1       0xFFFFFFFF   DECT-2020 NR - MAC                 1 Cluster beacon message
   222 5.361353270    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   223 6.190303875    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   224 7.205617815    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   225 8.186537063    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   226 9.132229625    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   227 *REF*          2       1            DECT-2020 NR - CVG                 1 Uplink message
   228 0.001653100    492     14289        DECT-2020 NR                       1 Acknowledgement message
   229 0.332689139    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   230 1.306452450    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   231 2.369206966    1       0xFFFFFFFF   DECT-2020 NR - MAC                 2 Network beacon message
   232 2.970790601    1       0xFFFFFFFF   DECT-2020 NR - MAC                 1 Cluster beacon message
```

```
Frame 214: 181 bytes on wire (1448 bits), 181 bytes captured (1448 bits)
DLT: 147, Payload: dectnr (DECT-2020 NR)
DECT-NR Metadata
    Header type: 2
    Radio channel: 1
DECT-2020 NR - PCC - Header type 2
    000. .... = Header format: 0
    ...0 .... = Packet length type: The length is given in subslots (0)
    .... 0101 = Packet length: 6 (5)
    0010 1111 = Short network address: 47
    0011 0111 1101 0001 = Transmitter identity: 14289
    0110 .... = Transmit power: -4 dBm (6)
    .... 0001 = DF MCS: 1
    0000 0001 1110 1100 = Receiver identity: 492
    00.. .... = Spatial streams: Single spatial stream (0)
    ..00 .... = DF Red. version: 0
    .... 1... = DF ind: 1
    .... .000 = DF HARQ Process Nr.: 0
    0000 .... = Feedback format: No feedback. Receiver shall ignore feedba
    .... 0000 0000 0000 = Feedback info: 0
DECT-2020 NR - MAC - v1.4.8
```

```
0000  01 01 05 2f 37 d1 61 01  ec 08 00 00 22 00 01 00
0010  00 00 01 00 00 00 02 10  10 00 00 00 07 43 78 20
0020  03 07 50 00 00 00 02 00  00 00 b7 1b 02 0a 0a 0d
0030  d4 00 00 00 00 01 02 03  04 05 06 07 08 09 0a 0b
0040  0c 0d 0e 0f 10 11 12 13  14 15 16 17 18 19 1a 1b
0050  1c 1d 1e 1f 20 21 22 23  24 25 26 27 28 29 2a 2b
0060  2c 2d 2e 2f 30 31 32 33  34 35 36 37 38 39 3a 3b
0070  3c 3d 3e 3f 40 41 42 43  44 45 46 47 48 49 4a 4b
0080  4c 4d 4e 4f 50 51 52 53  54 55 56 57 58 59 5a 5b
0090  5c 5d 5e 5f 60 61 62 19  03 00 40 14 00 00 00 00
00a0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00
00b0  00 00 00 00 00
```

```
DECT-2020 NR (dectnr), 2 bytes
```

__Figure 7.5.__ Inspection of random-access transmission and response between two simulated RDs.

Many requirements may be checked from the message exchange, one being the response transmission timing such that it occurs as signalled by the IUT in FT mode.

To verify whether the random-access response was done with correct timing, the position of the random-access response window needs to be calculated from the provided information. The $DECT\_Delay$ field included in the random-access resource IE defines how the beginning of the response window is calculated. When the $DECT\_Delay$ field is set to 1 the beginning of the response window is calculated as [18]:

$$n + HARQ\_delay + 1,$$

where n is the sub-slot where the RACH transmission ended, i.e., the packet length, $HARQ\_delay$ is the HARQ processing delay indicated in RD Capability IE during association in a previous message. The length of the response window is indicated in the Random-Access Resource IE of a cluster beacon message. This indicates the actual length of the response window minus one, e.g., (0 = 1 sub-slot).

For the simulation example, the $DECT\_Delay$ field is set to 1, and the values defining the beginning of the response window are: $n = 3$, $HARQ\_delay = 2$, $response\_window = 3$, thus making the response window begin after:

$$3 + 2 + 1 = 6 \text{ sub-slots}$$

Thus, the response must be transmitted within the sub-slots 7 to 10, relative to the beginning of the transmission. When using the lowest DECT-2020 NR numerology, i.e., having 2 sub-slots per slot, the response should be received between 1.250 ms and 2.083 ms.

The packet capture in Figure 7.5 shows the relative timing of the transmission–response pairs of two simulated RDs, and the response can be seen to be transmitted after 1.65 ms following the random-access transmission. This could thus be used to verify that the IUT is able to correctly indicate and respond with the correct timing.

7.3 Protocol conformance testing using physical test setups

For physical test setups where actual radio equipment is used, the target of testing is called the EUT. Some conformance requirements require the EUT to behave in a way that is not possible to be detected via any message contents but rather by observing the RDs behaviour on a physical radio channel using a spectrum analyser as the lower tester. Such behaviours are the result of the EUT conducting measurements on the RF spectrum.

The spectrum management procedures defined in the MAC layer specification [18] mostly rely on the received information acquired from a background scan, RSSI-1 measurement in this case, meaning any power detected on the measured frequency channel. Procedures measuring the link quality between another RD rely on the RSSI-2 measurement which indicates the strength of a successfully received signal.

Conducting conformance testing using a physical test setup requires a lot of fine-tuning the setup to be able to identify which transmissions belong to which RD. Additionally, many test purposes require their own unique setups, for which setting them up will consume a lot of time.

To demonstrate this, two setups are built to test the LBT, RD selection, and the mobility procedure.

7.3.1 Listen Before Talk (LBT)

Before any transmission to random-access resources, an RD needs to perform an LBT procedure [18]. The RD should measure the channel right before initiating transmission and decide whether the channel is free for transmission. If the channel is measured as busy, the RD retains from transmitting to the channel and performs the LBT again after a random time referred to as backoff. This is repeated until the EUT finds a free slot for its transmissions.

This paragraph describes a possible test implementation for the test purposes (1) and (2) defined in paragraph 6.3.4.

The LBT operation may be tested using a physical test setup, where the EUT can connect to an RD operating as a sink and is able to be interfered using a noise signal. The setup is similar to the harmonised standard test setup shown in Figure 5.1, except the roles of the RDs are reversed.

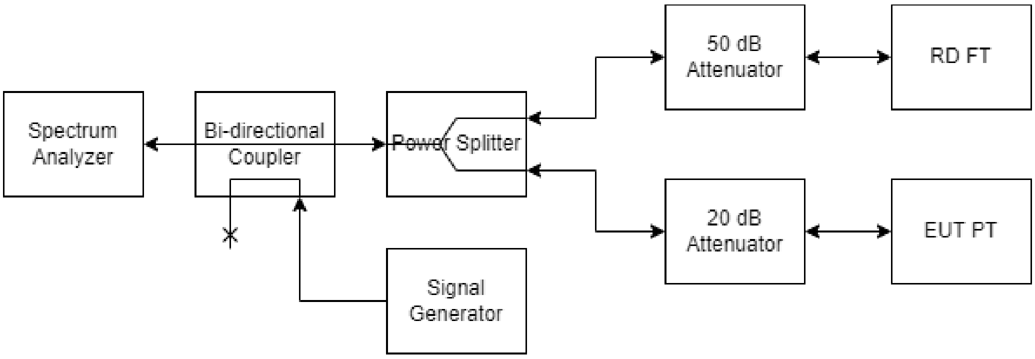


Figure 7.6. *Test setup used for testing the LBT protocol.*

In the test setup, the EUT is set to periodically transmit to the RD in FT mode by the upper tester/ test application. The signal generator (a lower tester) is used to produce interference which should force the EUT to retain from its transmissions.

The acquired spectrum analyser trace for defining the test verdict is shown in Figure 7.7 below.

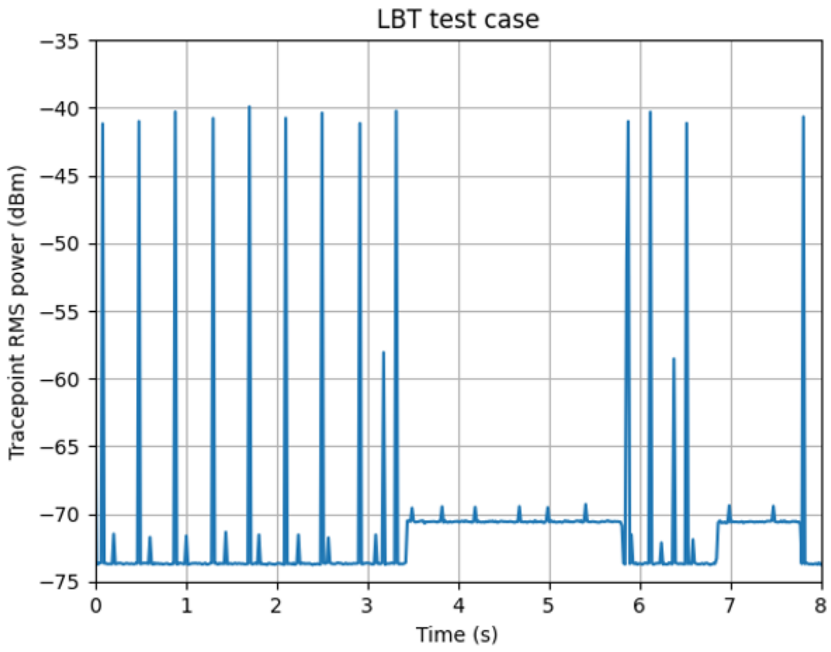


Figure 7.7. *Spectrum analyser trace for testing LBT protocol.*

In Figure 7.7, the highest power spikes depict the unicast transmissions the EUT is transmitting to the RD in FT mode. The other power spikes are transmissions from the RD in FT mode, the second highest being the cluster beacon messages and the lower ones are network beacon messages leaking from another channel.

The power levels seen in the spectrum analyser trace in Figure 7.7 do not indicate the actual power levels of the transmissions. The factors affecting the shown power level in the traces are explained in paragraph 5.2.2.

The applied interference can be seen as an increase of the noise floor, after which the EUT considers the channel as busy and retains from transmitting. When the interference is removed, the EUT measures the channel to be free and is again allowed to transmit to the RACH resources.

The behaviour seen in the Figure 7.7 would indicate a passing verdict for the test case.

7.3.2 RD selection for association

When an RD initiates the operation in PT mode, it should associate with an RD in FT mode which has the best route to sink. The requirements or suggestions are defined in the MAC layer specification. The related test purposes defined in this thesis are defined in paragraph 6.3.2.

The test setup includes two RDs operating as sinks to which the EUT may initiate association. By having a physically conducted test setup, the signal paths between RDs can be varied during the test.

To test the RD selection procedure, the setup show in Figure 7.8 is used.

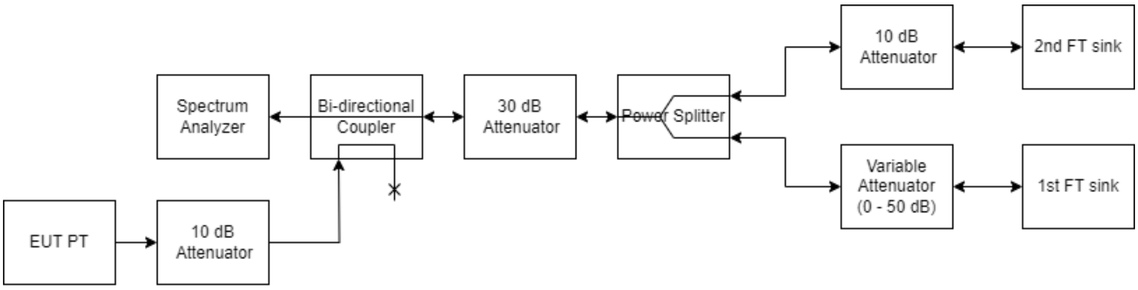


Figure 7.8. *Physical test setup for testing RD selection and mobility procedures.*

In the setup, the path from one sink is better than the other when the variable attenuator is set to $0\ \mathrm{dB}$, thus it should prefer the RD FT which provides a better RSSI-2 value since both RDs are sinks and should have identical route costs. The RD selection may be repeated by setting the variable attenuator attenuation to higher than $10\ \mathrm{dB}$, which would make the other sink a better option for the EUT.

To verify the RD selection, the EUT is configured to periodically transmit data packets to the sink. The packets are identified by monitoring the random-access channels of the RDs in FT mode with a spectrum analyser. It is again important to note that the powers seen at the EUT input differ from the levels seen at the spectrum analyser input, but the relative level between the power levels of the sinks remains the same.

The Figure 7.9 shows the network channel where both sinks are transmitting their network beacons. Since the network and cluster beacons are transmitted using the same transmission power, the power level of the network beacons can be used to identify their respective cluster beacons on another channel, and thus their operating channel.

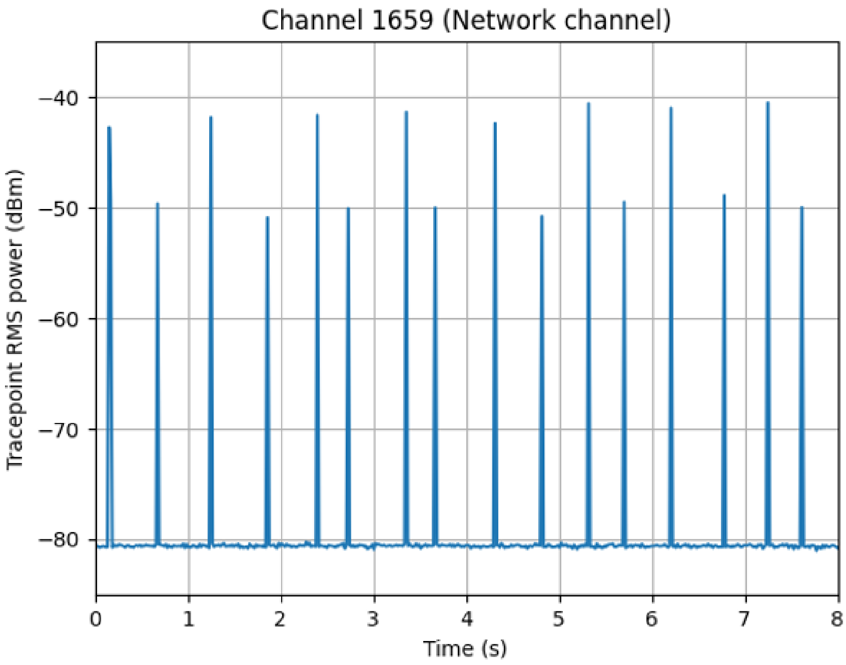


Figure 7.9. *The network beaconing of both sinks occurs on the same network channel.*

The Figure 7.9 shows the network beacons of both RDs operating as sinks. The $10\ \mathrm{dB}$ power difference caused by the attenuator towards the spectrum analyser can be clearly noticed, and thus the power levels can be associated with the sink devices and their cluster beacon transmissions. The higher power spikes indicating $\sim -40\ \mathrm{dBm}$ in Figure 7.9 can be associated with the RD named "1st FT sink" in Figure 7.8, and the lower ones indicating $\sim -50\ \mathrm{dBm}$ with the RD named "2nd FT sink".

The Figure 7.10 below shows a cluster beacon transmission on channel 1663. This can be identified as a cluster beacon since it is transmitted only once per the cluster beacon period of the EUTs.

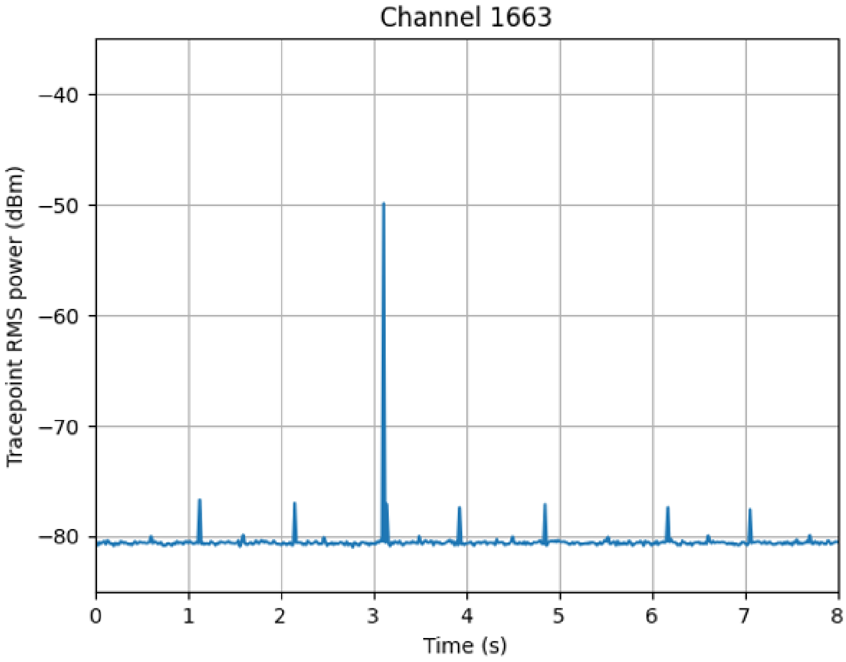


Figure 7.10. *Cluster beacon transmitted on the operating channel of the "2nd FT sink".*

The power spike in Figure 7.10 can be identified to belong to the RD named "2nd FT sink" in Figure 7.8, since the power level matches the power of its network beacon as stated above. Thus, the spectrum trace in Figure 7.10 shows the operating channel of the sink having the higher path loss. The observed channel shows no transmissions on it by the EUT, instead, some leakage from other channels can be seen.

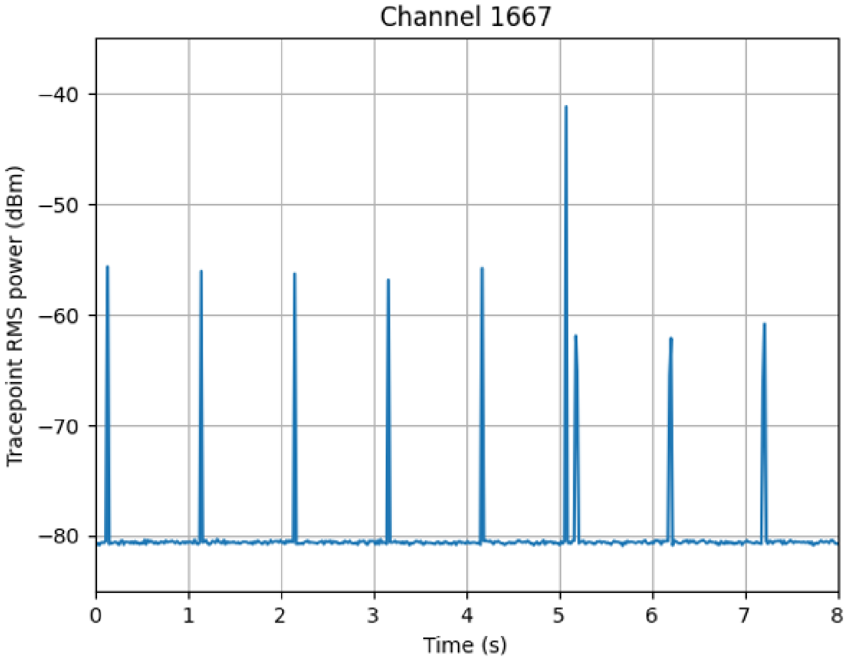


Figure 7.11. *Transmissions of the EUT and cluster beaconing of the "1st FT sink" on its operating channel.*

The Figure 7.11 shows periodic transmissions on channel 1667. This channel can be identified to be the operating channel of the “1st FT sink” from the power level of the highest power spike, i.e., the cluster beacon. The periodic transmissions occurring at 1-second intervals are caused by the EUT transmitting to the channel resources announced by the 1st sink. This suggests that the EUT has chosen the RD in FT mode which provides a better link quality.

7.3.3 Mobility procedure

This paragraph tests the mobility procedure of an RD. The test purposes are defined in paragraph 6.3.6.

By continuing from the RD selection test defined in paragraph 7.3.2 above and setting the variable attenuator such that the currently associated RD in FT mode has at least $\mathrm{RELATIVE\_QUALITY}$ [18] more attenuation than the other one, the EUT should consider changing the associated RD FT due to mobility. The values for $\mathrm{RELATIVE\_QUALITY}$ range from $0\ \mathrm{dB}$ to $9\ \mathrm{dB}$ with $3\ \mathrm{dB}$ steps [18]. The procedure may be tested by observing the operating channel where the sink having the initially weaker path is transmitting its cluster beacons.

After increasing the attenuation of the variable attenuator from $0\ \mathrm{dB}$ to $20\ \mathrm{dB}$, thus making the other channel $10\ \mathrm{dB}$ better, the EUT eventually changed the associated RD due to mobility after a few minutes. The MAC specification itself does not specify any time requirement related to this procedure. A spectrum analyser trace from the new stronger channel is shown below.

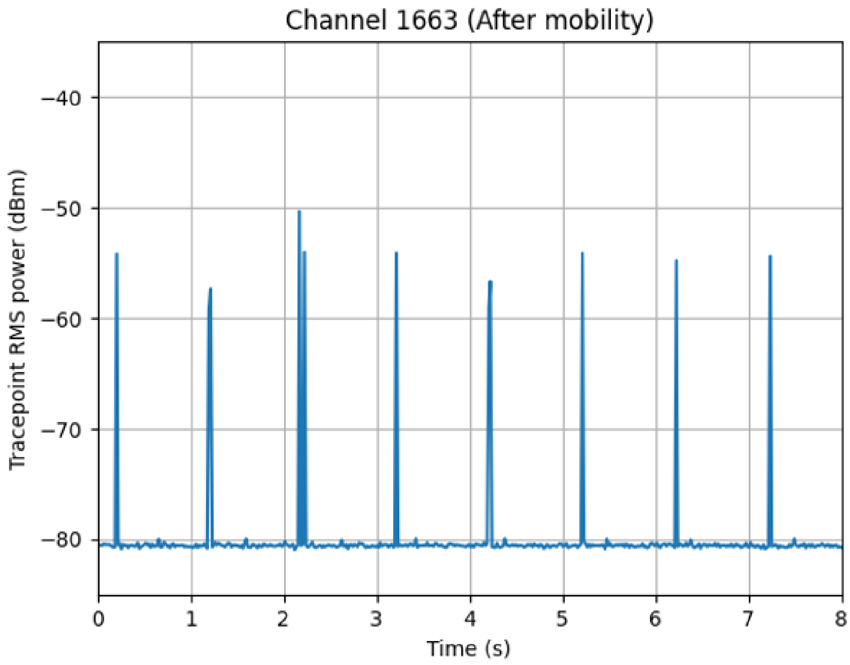


Figure 7.12. *EUT transmissions observed on the operating channel of "1st FT sink" after increasing the attenuation for "2nd FT sink".*

Figure 7.12 shows that the periodic EUT transmissions are occurring on the channel which initially provided the weaker beacon strength ($\sim -50\ \mathrm{dBm}$) after the RD selection tests shown in paragraph 7.3.2. Power spikes in Figure 7.12 occurring at 1-second intervals again depict the EUT transmissions, and the highest power spike depicts the cluster beacon transmission of the "1st FT sink" occurring once every 8 seconds.

The EUT can thus be considered to perform the mobility procedure when expected.

8. CONCLUSION

This thesis provided a look at the world of standardisation in the form of protocol testing, what testing specifications consist of and possible ways of testing protocol implementations in practice against requirements defined both in core specifications and regulations.

The radio technology for which the testing in this thesis was targeted was a recently published DECT-2020 NR standard designed for ultra-low latency and massive scalability in non-cellular networks. The technology allowed equal devices to communicate directly with each other while being able to operate either as the local coordinator or as the one being coordinated, enabling the possibility for mesh networks.

A harmonised standard for DECT-2020 NR had been published by ETSI to harmonise the testing methodology for a product implementing the DECT-2020 NR to reach regulatory compliance within the EU. This thesis used the methodology for testing channel access of a radio device implementing the forementioned technology in a random-access manner. Although the harmonised standard provided many other test methods as well, only the test methods related to functionalities controlled by the MAC protocol layer were in the scope of this thesis.

The goal of the harmonised standard and the related radio equipment directive requirement was to aim for efficient use of the radio spectrum and avoid interfering other users. This was reached in the channel access tests by the EUT in FT mode choosing its operating channel from a set of free channels and ensuring that when operating in PT mode, it correctly follows the instructions and only uses those resources which the device in FT mode coordinates. The tests required the EUT to stop using the spectrum when the coordinating device instructed so or was not able to instruct the EUT device.

These tests were conducted on a physical test setup against an actual product implementation and results indicating a conforming implementation were achieved. It was noticed that the methods described in the harmonised standard could be implemented with ease, assuming the test personnel has a certain degree of understanding about RF equipment and their capabilities, although requiring some tweaking of the reference setup and the parameterisation defined in the harmonised standard.

The latter part of the thesis introduced a set of new abstract test purposes. The test purposes were defined for functionalities that could be observed in any ordinary communication between two RDs using DECT-2020 NR. Thus, by having an implementation which achieves a positive verdict from the defined test purposes, the system would be capable of basic data exchange. The test purposes were abstract test descriptions, of how the protocol should behave in specific scenarios. These test purposes were derived from the conformance requirements of the core specification. For defining the tests, the standard needed to be carefully studied and its procedures understood on a detailed level to be able to identify the need for test purposes.

The test purposes were written using the ETSI standardised TPLan notation; however, it was not possible to define all the tests with the limited set of keywords which this notation offers, especially for functionalities not involving an observable semantic action, thus a freer wording was used for those.

This thesis additionally provided two example methods how these test purposes could be conducted without having any dedicated tester equipment: by using simulations, and physical test setups.

Due to the automatic operation of the DECT-2020 NR implementation, the behaviour for some of the basic interconnectivity functionalities could be observed by extracting a packet capture from a system simulation which included all transmitted packets during the simulation. The packet captures were parsed and analysed using the Wireshark packet analyser software, with a custom DECT-2020 NR parser plugin. The packet captures provided a possibility to inspect the message exchanges between simulated RDs on a bit level. This made it possible to manually compare the protocol behaviour against the conformance requirements.

The test examples using a physical setup and verifying them manually by observing specific patterns in the captured spectrum analyser traces proved to be a possible option for conducting conformance testing, although it was much more laborious than using simulations, just because the need to tweak the physical setup for every test.

The verdicts for these tests need to be defined based on the spectrum analyser traces, which relied a lot on knowing the configuration of the EUT, and how the test setup had an effect on the traces. Conformance testing using equipment such as signal generators and spectrum analysers proved to mainly be usable when the test method included checking whether a radio device is transmitting on a channel or not. This is a common aspect that could be noticed in both the harmonised standard testing and in the physical setup testing chapters of this thesis.

All in all, when defining a new radiocommunication standard, the standardisation work should also include the creation of testing specifications. The benefit of having standardised testing specifications can be considered to be that they are publicly available, readily made, and when defined well, they provide only a limited set of abstract tests can be used to assess conformity with the related standard such that an implementation will interwork with others also passing the same tests. The abstractness of the test definitions give room for manufacturers to implement the testing in a way that suits them the best.

The same benefits also apply to the harmonised standard tests, but with the difference of having specific test implementation requirements and resulting in a legal implementation.

Future considerations

As a future consideration, the harmonised standard tests could be automatised to have a rapid method for testing compliance whenever the software implementing the protocol is updated, while also preparing for the test implementation of the scheduled access tests also defined in the harmonised standard.

For the test purposes, the development work of the MAC layer tests will continue to cover the remaining procedures. To make a complete set of test definitions for the standard, conformance testing specifications need to include test purposes for all other protocol layers as well and have test suites developed for them. With new releases of the standard and profiles, the conformance specifications also need to be maintained to match their requirements.

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