ETSI TR 103 665 V1.1.1 (2021-05)

**System Reference document (SRdoc);
Data Transmission Systems using Wide Band technologies
in the 2,4 GHz band**

Reference
DTR/ERM-590

Keywords
radio, SRdoc

ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00   Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - APE 7112B
Association à but non lucratif enregistrée à la
Sous-Préfecture de Grasse (06) N° w061004871

Contents

Intellectual Property Rights

Essential patents

IPRs essential or potentially essential to normative deliverables may have been declared to ETSI. The declarations pertaining to these essential IPRs, if any, are publicly available for **ETSI members and non-members**, and can be found in ETSI SR 000 314: *"Intellectual Property Rights (IPRs); Essential, or potentially Essential, IPRs notified to ETSI in respect of ETSI standards"*, which is available from the ETSI Secretariat. Latest updates are available on the ETSI Web server (https://ipr.etsi.org/).

Pursuant to the ETSI Directives including the ETSI IPR Policy, no investigation regarding the essentiality of IPRs, including IPR searches, has been carried out by ETSI. No guarantee can be given as to the existence of other IPRs not referenced in ETSI SR 000 314 (or the updates on the ETSI Web server) which are, or may be, or may become, essential to the present document.

Trademarks

The present document may include trademarks and/or tradenames which are asserted and/or registered by their owners. ETSI claims no ownership of these except for any which are indicated as being the property of ETSI, and conveys no right to use or reproduce any trademark and/or tradename. Mention of those trademarks in the present document does not constitute an endorsement by ETSI of products, services or organizations associated with those trademarks.

DECT™, **PLUGTESTS™**, **UMTS™** and the ETSI logo are trademarks of ETSI registered for the benefit of its Members. **3GPP™** and **LTE™** are trademarks of ETSI registered for the benefit of its Members and of the 3GPP Organizational Partners. **oneM2M™** logo is a trademark of ETSI registered for the benefit of its Members and of the oneM2M Partners. **GSM**® and the GSM logo are trademarks registered and owned by the GSM Association.

Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

The present document contains necessary information to support the co-operation under the MoU between ETSI and the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT).

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

"**must**" and "**must not**" are **NOT** allowed in ETSI deliverables except when used in direct citation.

Introduction

The present document describes various existing as well as new types of Data Transmission Systems using Wide Band technologies in the 2,4 GHz band. These systems are further referred to as Wideband Data Transmission Systems in the present document. Examples of existing Wideband Data Transmission Systems are equipment based on industry standards such as IEEE Std. 802.11™-2016 RLANs [i.10], Bluetooth® [i.26] wireless technologies, IEEE 802.15.4™-2020 [i.12], Zigbee® [i.21], etc.

The present document was developed by ETSI TC ERM in response to a specific request made by CEPT WGFM during their February 2019 meeting. The information contained in the present document will allow the WGFM to decide whether the 2,4 GHz entry in ERC Recommendation 70-03 [i.1], Annex 3 for Wideband Data Transmission Systems in the frequency range 2 400 MHz to 2 483,5 MHz needs to be revised within the context of the revision of the EC Decision 2006/771/EC [i.2].

Executive summary

The present document is a response to a request from WG-FM for a consolidated ETSI view regarding a review of the regulations for the 2,4 GHz band. The present document describes existing regulations for this band and the harmonised standard ETSI EN 300 328 [i.5] to [i.8] which is based on the regulation. The present document also describes the major WDTS technologies used in the 2,4 GHz band as well as the relationship between ETSI EN 300 328 [i.5] to [i.8] and compliant products available on the EU market. In some cases, the present document presents challenges and potential challenges faced by implementors of WDTS.

The proponents of the present document consider that it is adequate for the purposes of WG-FM and the review of the 2,4 GHz regulations.

Other members of ETSI consider that the present document does not present WG-FM with sufficient information for its review of 2,4 GHz regulations. It presents summary of the status quo and the benefits of compliance with ETSI EN 300 328 [i.5] to [i.8], notably with regard to sharing the 2,4 GHz band; it presents industry standards as compliant without the clarification that industry standards never specify regulatory requirements; therefore the compliance described in the present document applies only to products sold in the EU and not to the technologies described.

Further, it is noted that ETSI EN 300 328 [i.5] to [i.8] defines a number of spectrum related requirements that are not based on regulatory requirements but have resulted from many years of give-and-take between industry members rather than from ECC spectrum sharing studies.

1 Scope

The present document describes the current Wideband Data Transmission Systems (WDTS) and technologies that have been developed over time compliant with the existing provisions in Annex 3 of ERC Recommendation 70-03 [i.1] for the 2,4 GHz band. In addition to using wideband modulation techniques, these systems use a polite access/sharing mechanism (which also includes mechanisms restricting the Medium Utilization) in order to facilitate sharing among the wide variety of Wideband Data Transmission Systems operating in this band. The details of the polite access/sharing mechanisms are described in ETSI EN 300 328 (V2.2.2) [i.8]. Products using these technologies that are available in Europe are required to be compliant with the existing provisions in EC Decision 2006/771/EC [i.2] or national regulations based on the ERC Recommendation 70-03 [i.1].

For the various Wideband Data Transmission Systems covered by the present document, the following information is included:

- Market information.
- Technical information [including expected sharing and compatibility issues].
- Regulatory issues.

The information on the various Wideband Data Transmission Systems in the present document can be used to support the work within CEPT in the context of updating the EC Decision 2006/771/EC [i.2].

During the time the present document was developed, no proposals for new systems were submitted. However, it was mentioned new systems are being developed which may lead to a future activity to revise the present document or to develop a new System Reference document.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

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

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

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

[i.1] ERC Recommendation 70-03 (12 June 2020): "Relating to the use of Short Range Devices (SRD)".

[i.2] Commission Decision 2006/771/EC of 9 November 2006 on harmonisation of the radio spectrum for use by short-range devices.

[i.3] Commission Decision 2009/381/EC of 13 May 2009 amending Decision 2006/771/EC on harmonisation of the radio spectrum for use by short-range devices.

[i.4] Commission Implementing Decision (EU) 2019/1345 of 2 August 2019 amending Decision 2006/771/EC updating harmonised technical conditions in the area of radio spectrum use for short-range devices.

[i.5] ETSI EN 300 328 (V1.4.1): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Wideband Transmission systems; Data transmission equipment operating in the 2,4 GHz ISM band and using spread spectrum modulation techniques; Harmonized EN covering essential requirements under article 3.2 of the R&TTE Directive".

[i.6] ETSI EN 300 328 (V1.7.1): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz ISM band and using wide band modulation techniques; Harmonized EN covering essential requirements under article 3.2 of the R&TTE Directive".

[i.7] ETSI EN 300 328 (V1.8.1): "Electromagnetic compatibility and Radio spectrum Matters (ERM); Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz ISM band and using wide band modulation techniques; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive".

[i.8] ETSI EN 300 328 (V2.2.2) (2019-07): "Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz band; Harmonised Standard for access to radio spectrum".

[i.9] ETSI EN 300 440 (V2.2.1): "Short Range Devices (SRD); Radio equipment to be used in the 1 GHz to 40 GHz frequency range; Harmonised Standard for access to radio spectrum".

[i.10] IEEE Std. 802.11™-2016: "IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.11] IEEE P802.11ax™/D7.0: "Draft Standard for Information Technology- Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific Requirements. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment 1: Enhancements for High Efficiency WLAN".

[i.12] IEEE 802.15.4™-2020: "IEEE Standard for Low-Rate Wireless Networks".

[i.13] IEEE 802.15.4™-2015: "IEEE Standard for Low-Rate Wireless Networks".

[i.14] IEEE 802.15.4™-2011: "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)".

[i.15] IEEE 802.15.4™-2006: "IEEE Standard for Information technology -- Local and metropolitan area networks -- Specific requirements -- Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs)".

[i.16] Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity (R&TTE Directive).

[i.17] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC.

[i.18] ERC Recommendation 74-01: "Unwanted Emissions in the Spurious Domain".

[i.19] EN 62591: 2016: "Industrial Communications Networks - Wireless Communication Network and Communication Profiles - WirelessHART".

[i.20] ECC Report 268: "Technical and Regulatory Aspects and the Needs for Spectrum Regulation for Unmanned Aircraft Systems (UAS)".

[i.21] ZigBee®: "The ZigBee Specification r21, 5 August 2015".

[i.22] EN 16836-2: 2016: "Communication systems for meters - Wireless mesh networking for meter data exchange - Part 2: Networking layer and stack specification" (produced by CENELEC).

[i.23] EN 16836-3: 2016: "Communication systems for meters - Wireless mesh networking for meter data exchange - Part 3: Energy profile specification dedicated application layer" (produced by CENELEC).

[i.24] Thread 1.1.1: "Thread 1.1.1 Specification, 13 February 2017".

[i.25] Thread 1.2: "Thread 1.2.0 Specification, 18 June 2019".

[i.26] Bluetooth® v5.2: "Bluetooth Core Specification 5.2", 31 December 2019.

[i.27] Bluetooth® v5.1: "Bluetooth Core Specification 5.1", 21 January 2019.

[i.28] Bluetooth® v5.0: "Bluetooth Core Specification 5.0", 6 December 2016.

[i.29] Bluetooth® v4.2: "Bluetooth Core Specification 4.2", 2 December 2014.

[i.30] Bluetooth® v4.1: "Bluetooth Core Specification 4.1", 3 December 2013.

[i.31] Bluetooth® v4.0: "Bluetooth Core Specification 4.0", 30 June 2010.

[i.32] IEC 62591:2016: "Industrial networks - Wireless communication network and communication profiles - WirelessHARTTM".

[i.33] IEC 62734:2014/AMD1:2019: "Amendment 1 - Industrial networks - Wireless communication network and communication profiles - ISA100.11a".

[i.34] Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91.

[i.35] Commission Delegated Regulation (EU) 2019/945 of 12 March 2019 on unmanned aircraft systems and on third-country operators of unmanned aircraft systems.

[i.36] Commission Implementing Regulation (EU) 219/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft.

[i.37] ETSI ETS 300 328 (November 1994): "Radio Equipment and Systems (RES); Wideband transmission systems; Technical characteristics and test conditions for data transmission equipment operating in the 2,4 GHz ISM band and using spread spectrum modulation techniques".

[i.38] IEEE 802.11b™-1999: "IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and Metropolitan networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher Speed Physical Layer (PHY) Extension in the 2,4 GHz band".

[i.39] Commission Implementing Decision of 4.8.2015 on a standardisation request to the European Committee for Electrotechnical Standardisation and to the European Telecommunications Standards Institute as regards radio equipment in support of Directive 2014/53/EU of the European Parliament and of the Council.

[i.40] IEEE 802.15.1™-2002: "IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements, Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANS)".

[i.41] IEEE 802.15.4™-2003: "IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 15: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPAN)".

[i.42] https://www.wi-fi.org/news-events/newsroom/wi-fi-global-economic-value-reaches-196-trillion-in-2018.

[i.43] https://www.bluetooth.com/learn-about-bluetooth/bluetooth-technology/range/.

[i.44] https://www.abiresearch.com/press/wi-fi-celebrates-20-years-more-20-billion-anticipated-device-shipments-over-next-six-years/.

[i.45] https://www.bluetooth.com/bluetooth-resources/2019-bluetooth-market-update.

[i.46] https://www.prnewswire.com/news-releases/global-zigbee-module-market-2018-2023-key-players-are-atmel-digi-nxp-semiconductors-renesas-electronics-silicon-laboratories-stmicroelectronics-texas-instruments-and-telink-semiconductor-300637272.html.

[i.47] https://onworld.com/news/1-Billion-802.15.4-Chipset-Shipments-by-2024.html.

[i.48] https://www.marketresearchfuture.com/reports/zigbee-market-2617.

[i.49] IETF RFC 4944: "Transmission of IPv6 Packets over IEEE 802.15.4 Networks".

[i.50] IETF RFC 6282: "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the terms given in ETSI EN 300 328 (V2.2.2) [i.8] apply.

3.2 Symbols

For the purposes of the present document, the symbols given in ETSI EN 300 328 (V2.2.2) [i.8] and the following apply:

kb/s	kilobits per second
Mb/s	Megabits per second
ms	millisecond
Msym/s	Mega Symbols per second
s	second
µs	microsecond

3.3 Abbreviations

For the purposes of the present document, the abbreviations given in ETSI EN 300 328 (V2.2.2) [i.8] and the following apply:

AMP	Alternate Mac-Phy
AoA	Angle of Arrival
AoD	Angle of Departure
APC	Adaptive Power Control
BER	Bit Error Rate
BR	Basic Rate
C2	Command and Control
CHIP	Connected Home over IP Project
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DPSK	Differential Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
DQPSK	Differential Quadrature Phase Shift Keying
EDR	Enhanced Data Rate
FEC	Forward Error Correction
GFSK	Gaussian Frequency Shift Keying
HW	HardWare
IoT	Internet of Things
IPv6	Internet Protocol (version 6)
ISA	International Society of Automation
LE	Low Energy

LECIM	Low Energy Critical Infrastructure Monitoring
MAC	Medium Access Control
MWS	Mobile Wireless Standards
OJEU	Official Journal of the European Union
QPSK	Quadrature Phase Shift Keying
PAN	Personal Area Network
PCA	Priority Channel Access
PCB	Printed Circuit Board
PDU	Protocol Data Unit
PHY	PHysical Layer
PIFA	Planar Inverted-F Antenna
RFID	Radio Frequency IDentification
RS-232	Recommended Standard 232
SIG	Bluetooth Special Interest Group
SRD	Short Range Device
SRD/MG	Short Range Device Maintenance Group
TCAM	Telecommunication Conformity Assessment and Market Surveillance Committee
TSCH	Time Slotted Channel Hopping
UAS	Unmanned Aircraft System
UDP	User Datagram Protocol
WDTS	Wideband Data Transmission Systems
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks

4 Comments on the System Reference Document

4.1 Comments from ETSI members

4.1.1 Qorvo Utrecht B.V.

"*Qorvo Utrecht B.V. represents the Wireless Connectivity Division (WCON) of Qorvo Inc., who is a global supplier of RF components and products that span a wide range of applications covering space, military and commercial and consumer use. Qorvo WCON is located in the Netherlands and supplies the industry with solutions for a variety of communication products, many of which are based on industry standards, e.g. Wi-Fi, Zigbee and Bluetooth.*

This Systems Reference Document was put together in response to a request from CEPT's WG-FM for an ETSI view on the update of the regulation for the 2.4GHz band as part of the regular update of the EC's SRD Regulation. The document describes the status quo in terms of how well SRD technologies fit with ETSI's harmonized standard ETSI EN 300 328 rather than providing a forward-looking perspective on how these technologies could develop under updated regulatory requirements. Convergence on an agreed content describing current technologies as well as the challenges these technologies face in their further development proved not possible.

Towards the end of the drafting of this document it was noted that ECC PT1, since September 2020, has two work items (PT1_28 and PT1_29) to investigate the revision of the technical conditions for MFCN operating in the range 2,300 to 2,400MHz to allow the introduction of 5G NR technology and to draft an ECC Decision on that subject. Although the details remain to be worked out, the main change being considered is related to the introduction of AAS technology with a potential gain of up to 20dB and the use of TRP metrics. Potentially, this change in the regulation will have major consequences for the SRDs operating in the 2,400 to 2,4835 MHz, e.g. through increased receiver blocking effects and through the increase in the noise floor. Given the regulatory status of the SRDs concerned, the increase in interference is unavoidable. However, changes in the regulatory requirements for SRDs that offer more possibilities to accommodate interference without increasing the average transmitted energy, would mitigate the impact.

Recognizing that the 2.4GHz sub-band for SRDs is intended for devices operating under general authorization - which implies no protection from any interference - we believe that the interests of the many users of the 2,4 GHz band are best served with a technology neutral regulatory regime that recognizes the expected changes in the MFCN regulation (see above) and that does not favour a specific technology or spectrum sharing mechanism but encourages innovation while facilitating shared use of this important resource.

This is a summary of our proposal for such a regime:

1) *Maintain the current RF power output limit of 100mW but measured as TRP over a suitable interval;*

2) *Adopt a single power spectral density limit of 100mW/MHz for all equipment,*

3) *Maintain the 10% medium utilization limit of ETSI EN 300 328 for non-adaptive devices with appropriate restrictions on transmitter activity and duty cycle,*

4) *Encourage the use of adaptive medium access techniques that exploit the three main parameters of spectrum use: power, time and frequency,*

5) *Encourage the use of spectrum efficient transmission techniques such as MIMO and beamforming.*

With regards to this Systems Reference Document, we feel it falls short of its intended purpose in the following ways:

1) *The document cites the SRD regulation and describes ETSI EN 300 328, the harmonised standard for Wideband Data transmission Systems (WDTS) as well as number of technologies and systems available in Europe. Emphasis is put on the "match" between the described technologies and the requirements of ETSI EN 300 328. Such a positive correspondence is to be expected since the technical requirements given in ETSI EN 300 328 determine the RF properties of products on the EU market. ETSI EN 300 328 represents de facto radio regulation since, when asked for an opinion on equipment, a Notified Body has no other reference than ETSI EN 300 328.*

2) *The SRD regulation differentiates between frequency hopping and non-frequency hopping modulation and it imposes a Power Spectral Density limit of 10 mW/MHz on the latter. This limit dates back to the 1990's; it was intended to facilitate co-existence of prospective technologies such as FHSS and DSSS. Since then, technology has moved on and dynamic methods of spectrum sharing render the old FHSS/DSSS separation superfluous. The 10mW/MHz limit does not affect systems using IEEE802.11 technology but it disadvantages other systems which have a lower bandwidth, e.g. using Bluetooth Low Energy or IEEE802.15.4 technology. This aspect is not addressed adequately in the document.*

3) *The document states repeatedly that the "Listen-Before-Talk" mechanism defined by ETSI EN 300 328 has been essential to the successful shared use of the 2.4GHz band and the widespread use of IEEE802.11 technology. This claim is not supported by fact or theory. The performance of the IEEE version of the LBT mechanism (and its DAA cousin) is adequate only within the scope and application of a single technology but it is not suitable in case multiple technologies are involved and does not support fair and efficient sharing of spectrum among different technologies with different power levels and bandwidths. In fact, no single mechanism like LBT is able to play that role in a mixed technology environment.*
That the 2.4GHz band remains one of the premier SRD bands worldwide testifies to the inventiveness of industry in developing spectrum sharing mechanisms that are effective - notably CSMA/CA as in IEEE Std. 802.11 and in IEEE 802.15.4 and the Adaptive Frequency Hopping technology developed for Bluetooth. These mechanisms are necessarily RF aware but the key to their effectiveness is not the LBT mechanism as such but the intelligence built into devices and products that allows them to exploit all three parameters of spectrum usage: power, time and frequency."

5 Regulations

5.1 ERC Recommendation 70-03

5.1.1 Annex 3 - 2,4 GHz Wideband Data Transmission Systems

ERC Recommendation 70-03 [i.1] sets out the general position on common spectrum allocations for Short Range Devices for countries within the CEPT. 2,4 GHz Wideband Data Transmission Systems are covered by frequency band b in Annex 3 of this Recommendation.

Table 1 is an extract out of table 3 from Annex 3 of this regulation only covering the 2,4 GHz band.

Table 1: Extract from Annex 3 of ERC Recommendation 70-03

	Frequency Band	Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation/ maximum occupied bandwidth	ECC/ERC deliverable	Notes
b	*2400.0-2483.5 MHz*	*100 mW e.i.r.p.*	*Adequate spectrum sharing mechanism (e.g. LBT and DAA) shall be implemented*	*Not specified*		*For wideband modulations other than FHSS, the maximum e.i.r.p. density is limited to 10 mW/MHz*

5.1.2 Annex 1 - Non-Specific Short Range Devices

The 2,4 GHz band is also covered by frequency band i in Annex 1 of ERC Recommendation 70-03 [i.1]. Annex 1 deals with Non-Specific Short Range Devices for which no application specific Annex exist in this Recommendation.

Table 2 is an extract out of table 1 from Annex 1 of ERC Recommendation 70-03 [i.1] only covering the 2,4 GHz band.

Table 2: Extract from Annex 1 of ERC Recommendation 70-03

	Frequency Band	Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation/ maximum occupied bandwidth	ECC/ERC deliverable	Notes
i	*2400.0-2483.5 MHz*	*10 mW e.i.r.p.*	*No requirement*	*Not Specified*		*The frequency band is also identified in Annexes 3 and 6*

The main difference between both entries is that power level for the generic short range devices (Annex 1) is restricted to 10 mW e.i.r.p. while the power level for WDTS (Annex 3) is 100 mW e.i.r.p. However, in order to use this higher power, devices have to use a spectrum sharing mechanism in addition to either implement frequency hopping or a restriction on the Power Spectral Density in order to qualify as a WDTS system.

Information in this clause is only provided for reference (comparison), it is further not used in the present document.

5.1.3 Annex 6 - Radiodetermination Applications

The 2,4 GHz band is also covered by frequency band c in Annex 6 of ERC Recommendation 70-03 [i.1]. Annex 6 deals with Radiodetermination Applications.

Table 3 is an extract out of table 6 from Annex 6 of this regulation only covering the 2,4 GHz band.

Table 3: Extract from Annex 6 of ERC Recommendation 70-03

	Frequency Band	Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation/ maximum occupied bandwidth	ECC/ERC deliverable	Notes
c	*2400.0-2483.5 MHz*	*25 mW e.i.r.p.*	*No requirement*	*Not Specified*		

Information in this clause is only provided for reference (comparison), it is not used further in the present document.

5.1.4 Annex 11 - Radio Frequency Identification Applications

The 2,4 GHz band is also covered by frequency bands c1 and c2 in Annex 11 of ERC Recommendation 70-03 [i.1]. Annex 11 deals with Radio Frequency Identification Applications.

Table 4 is an extract out of table 11 from Annex 11 of this regulation only covering (part of) the 2,4 GHz band.

Table 4: Extract from Annex 11 of ERC Recommendation 70-03

Frequency Band		Power / Magnetic Field	Spectrum access and mitigation requirements	Modulation/ maximum occupied bandwidth	ECC/ERC deliverable	Notes
c1	*2446-2454 MHz*	*≤ 500 mW e.i.r.p.*	*No requirement*	*Not Specified*		
c2	*2446-2454 MHz*	*> 500 mW to 4 W e.i.r.p.*	*≤ 15% duty cycle FHSS techniques should be used*	*Not Specified*		*Power levels above 500 mW are restricted to be used inside the boundaries of a building and the duty cycle of all transmissions shall in this case be ≤ 15 % in any 200 ms period (30 ms on /170 ms off)*

Information in this clause is only provided for reference (comparison), it is further not used in the present document.

5.2 Commission Decision 2006/771/EC

Commission Decision 2006/771/EC [i.2] harmonises the technical conditions for use of spectrum for a wide variety of short-range devices among the member states of the European Union. While the usage of the 2,4 GHz band by generic short range devices was included from its initial release in 9 November 2006, 2,4 GHz 'Wideband data transmission Systems' were added on 13 May 2009 via Commission Decision 2009/381/EC [i.3] amending Decision 2006/771/EC [i.2].

Commission Decision 2006/771/EC [i.2] was last modified by Commission Implementing Decision (EU) 2019/1345 of 2 August 2019 [i.4]. Table 5 contains an extract from table 2 in the Annex to this Commission Decision with the relevant 2,4 GHz entries for Non-specific short range devices (band 57a), Radio determination (band 57b), Wideband data transmission devices (band 57c) and for Radio Frequency Identification (band 58).

Table 5: Extract from Commission Decision 2006/771/EC [i.2]

Band no	*Frequency band*	*Category of short-range devices*	*Transmit power limit/field strength limit/power density limit*	*Additional parameters (channelling and/or channel access and occupation rules)*	*Other usage restrictions*	*Implementation deadline*
57a	*2 400-2 483,5 MHz*	*Non-specific short-range devices (3)*	*10 mW equivalent isotropic radiated power (e.i.r.p.)*			*1 July 2014*
57b	*2 400-2 483,5 MHz*	*Radio determination devices*	*25 mW e.i.r.p.*			*1 July 2014*
57c	*2 400-2 483,5 MHz*	*Wideband data transmission devices [16]*	*100 mW e.i.r.p. and 100 mW/100 kHz e.i.r.p. density applies when frequency hopping modulation is used, 10 mW/MHz e.i.r.p. density applies when other types of modulation are used*	*Requirements on techniques to access spectrum and mitigate interference apply [7].*		*1 July 2014*
58	*2 446-2 454 MHz*	*Radio Frequency Identification (RFID) devices*	*500 mW e.i.r.p.*	*Requirements on techniques to access spectrum and mitigate interference apply [7]*		*1 July 2014*
[7]	*Techniques to access spectrum and mitigate interference that provide an appropriate level of performance to comply with the essential requirements of Directive 2014/53/EU shall be used. If relevant techniques are described in harmonised standards or parts thereof the references of which have been published in the Official Journal of the European Union under Directive 2014/53/EU, performance at least equivalent to these techniques shall be ensured.*					

For references used in table 5 and which were not added into the table above, please consult Annex 2 of Commission Decision 2006/771/EC [i.2].

Similar to the ERC Recommendation 70-03 [i.1], Wideband data transmission devices referred to in band 57c are allowed to use an output power of 100 mW e.i.r.p. but they are subject to additional requirements/restrictions when compared to Non-specific short range devices which may only use an output power of 10 mW e.i.r.p. however with no further restrictions.

According to the Commission Decision 2006/771/EC [i.2] "*Wideband data transmission devices covers radio devices that use wideband modulation techniques to access the spectrum*".

6 Harmonised Standard

6.1 ETSI EN 300 440

ETSI EN 300 440 [i.9] is a generic harmonised standard covering a wide range of Short Range Devices operating in frequency bands within the range 1 GHz to 40 GHz. This standard covers the following devices operating in (parts of) the 2 400 MHz to 2 483,5 MHz band:

- Non-Specific Short Range Devices: see clause 5.1.2.
- Radiodetermination Applications: see clause 5.1.3.

- Radio Frequency Identification Applications: see clause 5.1.4.

When comparing the requirements for 2,4 GHz non-specific short range devices specified in ETSI EN 300 440 [i.9] and the requirements for Wideband Data Transmission Systems specified in ETSI EN 300 328, the main difference is the higher power (100 mW e.i.r.p.) allowed in ETSI EN 300 328 (V2.2.2) [i.8] provided that devices comply with Medium Utilization or Adaptivity, in addition a Power Spectral Density restriction applies to non-FHSS equipment. These requirements or restrictions do not exist in ETSI EN 300 440 [i.9] for non-specific short range devices in the 2,4 GHz band, but as a consequence the maximum power is limited to 10 mW e.i.r.p.

6.2 ETSI EN 300 328

6.2.1 Introduction

ETSI EN 300 328 (V2.2.2) [i.8] is the applicable standard for 2,4 GHz Wideband Data Transmission Systems. This standard is referenced in Annex 3 of ERC Recommendation 70-03 [i.1] for band b (2 400,0 MHz to 2 483,5 MHz). This standard is also applicable for devices covered by band 57c of Commission Decision 2006/771/EC [i.2].

The current version of this standard which is listed in the OJEU (February 5, 2020) is ETSI EN 300 328 (V2.2.2) [i.8]. This was the second version listed under Directive 2014/53/EU [i.17].

The first edition of this standard was published by ETSI in November 1994 as ETSI ETS 300 328 [i.37]. In July 2000 the standard was split into 2 parts out of which part 2 became the Harmonised Standard under the Directive 1999/5/EC [i.16]. Starting from ETSI EN 300 328 (V1.4.1) [i.5] the standard became a single part harmonised standard and remained as such during further revisions.

6.2.2 Equipment types in ETSI EN 300 328

6.2.2.1 Introduction

The Commission Decision 2006/771/EC [i.2] defines Wideband data transmission devices as radio devices that use wideband modulation techniques to access spectrum. Band 57c of this decision further distinguishes between devices using Frequency Hopping modulation and devices using other types of wide band modulation, further referred to as non-Frequency Hopping devices.

6.2.2.2 Frequency Hopping devices

Frequency Hopping is a Spread Spectrum technology which can share a frequency band with many other frequency hopping devices with minimal interference. Frequency Hopping is a method of transmitting signals by switching the carrier frequency among many frequency channels, using a pseudorandom sequence known to both the transmitter and the receiver. This spreading allows multiple frequency hopping systems to share the same frequency range without coordination. It also reduces detectability and improves robustness against interference from other spectrum users, including other frequency hopping systems. Hopping over wider frequency range improves these properties. The interference caused into non-hopping systems depends on the frequency range over which the hopping occurs and the bandwidth of the victim: a wider bandwidth of the latter increases the probability of receiving interference from other systems.

Frequency Hopping devices have no restriction on the Power Spectral Density but in order to qualify as a Frequency Hopping device, the standard specifies Frequency Hopping specific requirements such as maximum Accumulated Transmit Time, minimum Frequency Occupation, Hopping Sequence (minimum number of hopping frequencies) and minimum Hopping Frequency Separation. In addition, the maximum Occupied Channel Bandwidth is also limited to 5 MHz for non-adaptive Frequency Hopping systems.

Frequency hopping can be used in combination with Medium Utilization (see clause 6.2.3.2) or Adaptivity (see clause 6.2.3.3) to reduce the interference into other systems operating in the same band. The use of Medium Utilization or Adaptivity is mandatory for power levels above 10 mW e.i.r.p.

6.2.2.3 Non-Frequency Hopping devices

While Frequency Hopping devices have no restriction on the Power Spectral Density, non-frequency hoppers have to respect a restriction of the Power Spectral Density. This will force systems that operate at the maximum power, to spread their energy over a wider frequency range, compared to a Frequency Hopping system when considering a single hopping frequency.

Often non-frequency hopping devices have also implemented Adaptivity (see clause 6.2.3.3) in order to facilitate sharing with other users of the band. Typical examples are IEEE Std. 802.11 [i.10] devices and IEEE 802.15.4 devices which implement CSMA/CA, an LBT based medium access mechanism. As an alternative to Adaptivity, non-frequency hopping devices can also implement Medium Utilization (see clause 6.2.3.3) as a means to facilitate sharing with other users of the band. The use of Medium Utilization or Adaptivity is mandatory for power levels above 10 mW e.i.r.p.

6.2.3 Access & Mitigation techniques in ETSI EN 300 328

6.2.3.1 Introduction

The Commission Decision 2006/771/EC [i.2] mandates the use of *"techniques to access spectrum and mitigate interference"* for Wide Band Data Transmission Systems in the 2,4 GHz band. Reference is made to relevant techniques described in the applicable harmonised standard.

In June 2008, TCAM concluded that this was insufficiently defined in ETSI EN 300 328 (V1.7.1) [i.6] and therefore ETSI was instructed to revise this version to include verifiable sharing mechanisms that would ensure equal access to the 2,4 GHz band for all devices within the scope of Sub-Class 22. This resulted in the most comprehensive revision of the standard during its history. In June 2012, ETSI published ETSI EN 300 328 (V1.8.1) [i.7] and in October 2013, this version was also listed in the OJEU. From the many changes made in version 1.8.1, the introduction of Adaptivity covering the mechanisms Listen Before Talk (LBT) and DAA (Listen After Talk - LAT) for adaptive equipment and the introduction of Medium Utilization covering requirements (restrictions) on Duty Cycle and/or RF Output Power for non-adaptive systems were the most important changes made to the standard. Compliance with this version 1.8.1 was mandated as of 1 January 2015.

Figure 1 below provides a graphical (flow-chart) presentation of how Adaptivity and Medium Utilization were included in version 1.8.1 for both frequency hopping and non-frequency hopping devices.

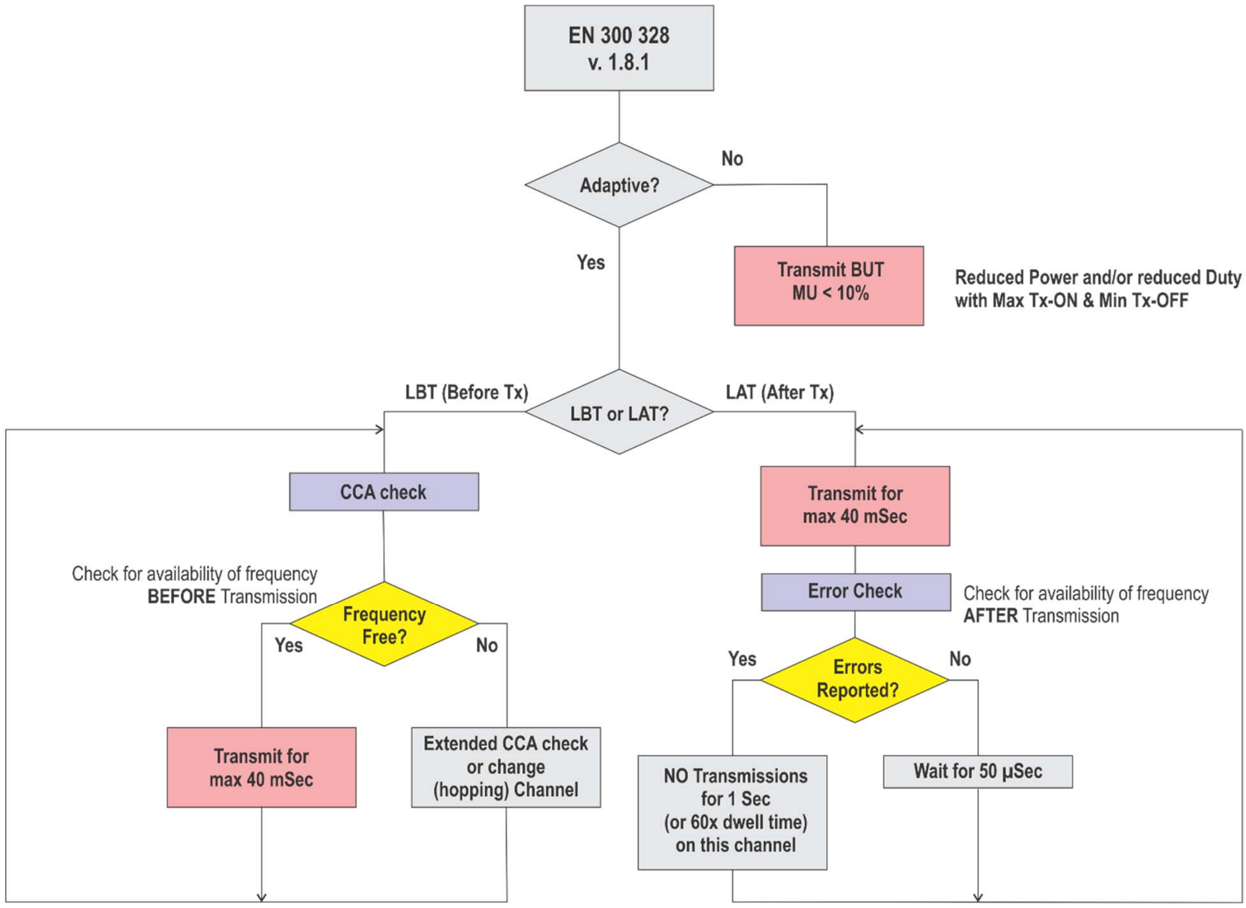

Figure 1: Access & Mitigation techniques in ETSI EN 300 328 (V1.8.1) [i.7]

6.2.3.2 Medium Utilization (non-Adaptive Systems)

6.2.3.2.1 Introduction

Medium Utilization was first introduced into ETSI EN 300 328 (V1.8.1) [i.7] as a simple alternative to Adaptivity and which could be implemented by devices that do not need the full resources of the medium in respect to time and power. A device transmitting 100 % of the time at the maximum allowed power will have a Medium Utilization of 100 %, restricting the Medium Utilization for non-adaptive systems to just a portion of that will enable multiple non-adaptive systems to use the same medium at a given location or will facilitate sharing with Adaptive systems.

Medium Utilization has been introduced for both Frequency Hopping and non-Frequency Hopping devices.

6.2.3.2.2 Medium Utilization of non-FHSS equipment or non-FHSS mode of operation

Devices operating on a fixed channel or frequency logically fall under the non-FHSS classification. The WDTS regulation imposes a PSD limit of 10 dBm/MHz e.i.r.p. Adding the bandwidth gives the following formula:

$$P_{out} = MAX(MIN(MU_{max} \times (OCBW \times PD_{max}/DC); P_{max});10) \text{ mW} \quad (1)$$

where: MU_{max} is the 10 % limit specified in ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.6.

OCBW is the occupied bandwidth.

DC is the Duty Cycle as defined in ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.3.2 expressed in %.

P_{out} is the RF output power as defined in clause ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.2.2 expressed in mW.

PD_{max} is the PSD limit for non-FHSS equipment given in the Commission Decision 2006/771/EC [i.2].

P_{max} is the EIRP limit given in the Commission Decision 2006/771/EC [i.2].

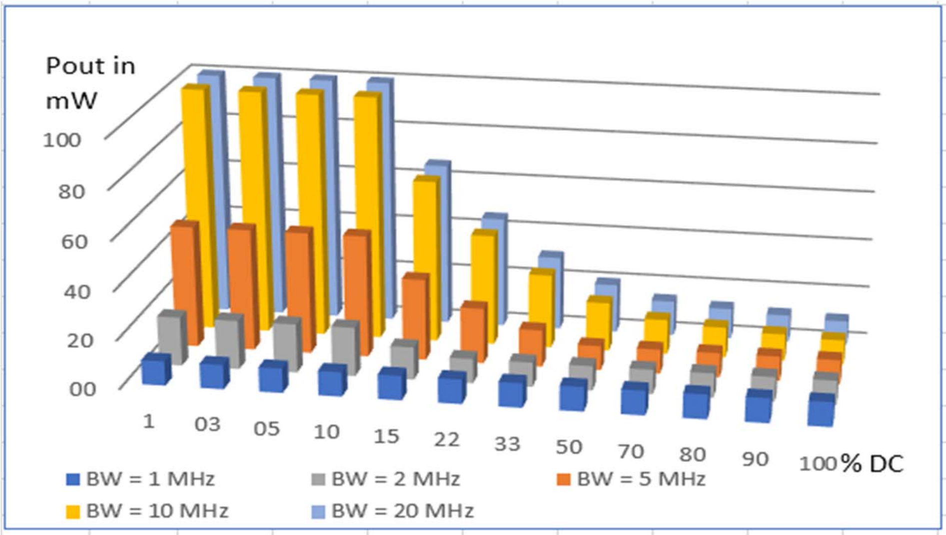

Figure 2: Non-FHSS, maximum power output as function of the duty cycle and bandwidth

The behaviour seen in figure 2 is in line with what was intended when MU was first introduced back in 2009. It was agreed that a reduction in bandwidth should not be rewarded as to maintain the incentive to spread the energy in the frequency domain. The Power Spectral Density limit helps to meet this objective.

6.2.3.2.3 Medium Utilization of FHSS equipment or mode of operation

FHSS devices and devices operating in FHSS mode are required (see ETSI EN 300 328 (V2.2.2) [i.8] clause 4.3.1.4.3.1) to use at least N = 5 or N = 15/hop frequency separation (defined in ETSI EN 300 328 (V2.2.2) [i.8] clause 4.3.1.5.3.1.), whichever is larger. In the following N=5 has been used:

$$P_{out} = MAX(MIN((MU_{max} \times (U/5) \times P_{max}/DC);P_{max});10)mW \quad (2)$$

where: P_{out} is the RF output power as defined in ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.2.2 expressed in mW.

MU_{max} is the 10 % limit specified in ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.6.

P_{max} is the EIRP limit given in the Commission Decision 2006/771/EC [i.2].

DC is the Duty Cycle as defined in ETSI EN 300 328 (V2.2.2) [i.8], clause 4.3.1.3.2 expressed in %.

U is the actual number of hop frequencies in use.

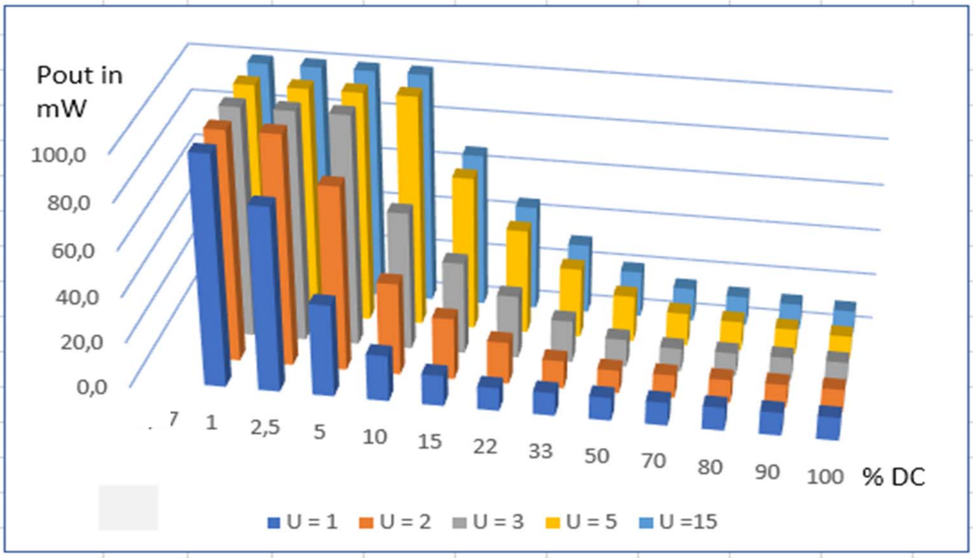

Figure 3: Maximum power output as function of the number of hops and duty cycle

The behaviour seen in figure 3 above is in line with what was intended when MU was first introduced back in 2009 for frequency hopping systems. It was agreed that a reduction in the number of frequency hopping positions should not be rewarded as to maintain the incentive to spread the energy in the frequency domain by using more hopping frequencies. This has the same objective as the Power Spectral Density requirement for non-hopping systems.

6.2.3.3 Adaptivity (Adaptive Systems)

At the same time that Medium Utilization was introduced (see clause 6.2.3.2.1) also Adaptivity was introduced into ETSI EN 300 328 (V1.8.1) [i.7]. As explained in clause 6.2.3.1, this was done on a specific request from TCAM who mandated all devices within sub-class 22 to use a polite sharing mechanism that had to be detailed in the harmonised standard.

The basic principle is that devices check the availability of the channel on which they (intend to) operate. The standard has included two options for checking the availability. Either this checking is done before a transmission (Adaptivity using LBT) or this checking is done after a transmission (Adaptivity using DAA - Listen After Talk). In both cases, the maximum time a device can transmit on a channel before it has to re-check the availability of that channel is limited. In case of Adaptivity using DAA, and the device has identified the channel to be occupied, the device has to remain silent on that channel for a defined period before it may have the next transmission in that channel. Adaptivity (LBT and DAA/LAT) has been introduced for both Frequency Hopping and non-Frequency Hopping devices. Although the actual sensing mechanism and the maximum transmission time may differ between these technologies, the level (detection threshold) that has to be used to sense the availability of a given channel is the same for all technologies.

6.2.4 Receiver categories in ETSI EN 300 328

6.2.4.1 Introduction

ETSI EN 300 328 (V2.2.2) [i.8] defines 3 receiver categories. This categorization is done based on whether the equipment is adaptive or non-adaptive equipment and on the medium utilization.

6.2.4.2 Receiver category 1

The following equipment is categorized as receiver category 1 equipment:

- Adaptive equipment with a maximum RF output power greater than 10 dBm e.i.r.p.

NOTE: Non-adaptive equipment is categorized as receiver category 2 or receiver category 3.

6.2.4.3 Receiver category 2

The following equipment is categorized as receiver category 2 equipment:

- non-adaptive equipment with a Medium Utilization (MU) factor greater than 1 % and less than or equal to 10 % (irrespective of the maximum RF output power); or
- equipment (adaptive or non-adaptive) with a maximum RF output power greater than 0 dBm e.i.r.p. and less than or equal to 10 dBm e.i.r.p.

6.2.4.4 Receiver category 3

The following equipment is categorized as receiver category 3 equipment:

- non-adaptive equipment with a maximum Medium Utilization (MU) factor of 1 % (irrespective of the maximum RF output power); or
- equipment (adaptive or non-adaptive) with a maximum RF output power of 0 dBm e.i.r.p.

7 Economic Value of license exempt spectrum

The advantage of license exempt spectrum is that any certified device can operate within it with only minimal restrictions placed upon the uses to which it may be put. By providing guaranteed and nonexcludable access to spectrum, license exempt spectrum encourages manufacturers to collaborate in the development of open standards, and to compete in the delivery of low-cost components and user equipment. The availability of mass-produced hardware and guaranteed access to spectrum has encouraged experimentation and innovation, leading to new products and models for service delivery. Some of these are mass-market successes, such as Bluetooth® and Wi-Fi®, whilst others are bespoke applications, targeting particular specialized markets.

The remarkable innovation seen in license exempt spectrum shows no sign of abating. ZigBee and Bluetooth Low Energy are vying to become the standard for short-range connectivity within homes and offices and will be increasingly encountered embedded in commonplace electronics and appliances. Combined with smart meters monitoring energy usage, these devices enable significant savings in power and improvements in the quality of life.

This innovation in license exempt spectrum is built on competition between thousands of manufacturers, service providers and systems integrators of varying scale and scope competing to sell a wide range of products and services directly to the end-user.

The economic value of a technology has two major components: on the one hand the value of the installed base and the value generated by installation services, etc., and on other hand, the value generated by the usage of that technology.

The technology specific sub-clauses in clause 8 contain more specific market information for each of the technologies.

8 Presentation of the various existing Wideband Data Transmission systems/technologies

8.1 IEEE Std. 802.11 technology (2,4 GHz Wi-Fi)

8.1.1 Introduction

In 1997, the IEEE Std. 802.11 [i.10] Working Group created its first wireless LAN standard. In 1999, the Wireless Ethernet Compatibility Alliance (WECA) was formed and this was later renamed to Wi-Fi Alliance® in 2002. The objective was to promote the IEEE Std. 802.11 [i.10] standard as Wi-Fi, with a focus on tested interoperability between devices from multiple vendors. At the time, the future success of Wi-Fi was uncertain, with a market generally limited to connecting laptops in enterprise environments. Since those early beginnings, Wi-Fi has taken a journey in which the standard has been continually refined by the IEEE Std. 802.11 [i.10] Working Group and interoperability testing expanded by the Wi-Fi Alliance to satisfy the needs of the market as it changed and expanded.

Today, Wi-Fi operates at 2,4 GHz and at 5 GHz which allows it to enable connectivity to billions of people and devices around the world at home, in public spaces and at work, for serious and not so serious applications. Wi-Fi is no longer limited to laptops. Today, Wi-Fi is included by default in just about every smartphone, tablet, and computer. It is also included in just about any device that needs to communicate wirelessly in a local area, from fitness trackers for individuals and Internet of Things (IoT) devices in factories to refrigerators and vehicles. It is used in homes by consumers, by enterprises for business and by service providers to complement the cellular network. It is even used in the International Space Station. The success of Wi-Fi is can be quantified in economic terms by studies which show WiFi has a global economic value of about two trillion dollars per annum.

The latest version of Wi-Fi is known as Wi-Fi 6 and is based upon the (draft) IEEE P802.11ax [i.11] standard. Wi-Fi 6 continues the tradition of each generation of Wi-Fi introducing new capabilities to effectively handle the expanding demands of the market. It provides improved performance, spectrum efficiency and throughput, particularly in the presence of interfering sources in dense networks, with heavily loaded APs, and indoor and outdoor deployments

The IEEE Std. 802.11 [i.10] standard defines 20 and 40 MHz channel bandwidths for the 2,4 GHz band.

Major elements that contributed to the success of the 2,4 GHz band are :

1) the global availability;

2) the simplicity of both the regulation and the compliance requirements; and

3) the band being license exempt.

This has allowed the evolution of the (voluntary) technical standard in terms of modulation, transmission protocol and medium access methods which resulted in the very capable Wi-Fi technology that has become a necessary element of daily life.

Typical use cases include: Home Wi-Fi, Smart cars and infotainment systems, Business/Enterprise, e-Learning, Internet of Things, Stadiums and venues, Transportation hubs and shopping malls, Healthcare and Industrial.

8.1.2 Technical description

8.1.2.1 Transmitter parameters

8.1.2.1.1 RF Output Power (e.i.r.p.)

IEEE Std. 802.11 [i.10] equipment used in different applications will have different power levels. Most devices are expected to use e.i.r.p. levels lower than the maximum limit for various reasons such as power consumption and transmit power control.

Devices that serve as access points may transmit at a higher power level than the devices that serve as mobile or portable (client) stations.

8.1.2.1.2 Power Spectral Density

IEEE Std. 802.11 [i.10] equipment has a Power Spectral Density in the 2,4 GHz band that is below the applicable regulatory limit of 10 dBm/MHz e.i.r.p. in any of its operational modes.

In practice, IEEE Std. 802.11 [i.10] equipment operating in 20 MHz mode has a maximum power in any one MHz which is about 10 dB to 13 dB below the measured RF Output Power when operating in that same mode. When operating in 40 MHz mode the maximum power in any one MHz is about 12 to 15 dB below the measured RF Output Power when operating in that same mode.

The Power Spectral Density requirement forces equipment to spread its energy in the frequency domain and as such reduces the potential of interference into other systems certainly if these other systems operate at a lower bandwidth.

8.1.2.1.3 Occupied Channel Bandwidth

IEEE Std. 802.11 [i.10] equipment operating in the 2,4 GHz band and when operating in a (draft) IEEE P802.11ax [i.11] 20 MHz mode, has an Occupied Channel Bandwidth of about 19 MHz. When operating in a (draft) IEEE P802.11ax [i.11] 40 MHz mode its Occupied Channel Bandwidth has increased to about 38 MHz.

Draft IEEE P802.11ax [i.11] allows a temporary use of narrower than 20 MHz BW for better spectrum efficiency while still complying with the 10 dBm/MHz e.i.r.p. PSD limit.

8.1.2.1.4 Channel Access Parameters

8.1.2.1.4.1 Duty Cycle

As IEEE Std. 802.11 [i.10] equipment is Load Based Adaptive equipment, there are no duty cycle restrictions defined in ETSI EN 300 328 (V2.2.2) [i.8].

8.1.2.1.4.2 Medium Utilization

As IEEE Std. 802.11 [i.10] equipment is Load Based Adaptive equipment, there are no restrictions on Medium Utilization defined in ETSI EN 300 328 (V2.2.2) [i.8].

8.1.2.1.4.3 Adaptivity (e.g. LBT)

IEEE Std. 802.11 [i.10] equipment is Load Based Adaptive equipment and therefore is subject to the Adaptivity requirement in ETSI EN 300 328 (V2.2.2) [i.8]. The LBT based mechanism of the IEEE Std. 802.11 [i.10] (CSMA/CA - Carrier Sense Multiple Access with Collision Avoidance) for channel access facilitates coexistence in case more devices use the same spectrum at the same location.

The CCA mechanism is defined slightly different in the various amendments of the IEEE Std. 802.11 [i.10] specification but it can be summarized as below:

A channel is considered busy if:

1) energy is being received above -62 dBm in a 20 MHz channel
2) an IEEE Std. 802.11 [i.10] signal is being received above -82 dBm in a 20 MHz channel
3) an IEEE Std. 802.11 [i.10] signal is being received above -79 dBm in a 40 MHz channel

The maximum transmission time (Channel Occupancy Time) is typically in the order of a few ms. The default maximum transmit opportunity limit specified in IEEE Std. 802.11 [i.10] is provided in table 6.

Table 6: Maximum transmission times for IEEE Std. 802.11 [i.10]

Access Category	802.11b	802.11g-OFDM, 802.11n, 802.11ax
Background	3,264 ms	2,528 ms
Best Effort	3,264 ms	2,528 ms
Video	6,016 ms	4,096 ms
Voice	3,264 ms	2,080 ms

8.1.2.1.5 Transmitter unwanted emissions

The limits for transmitter unwanted emissions defined in IEEE Std. 802.11 [i.10] are more stringent than those defined in ETSI EN 300 328 (V2.2.2) [i.8] by more than 10 dB.

8.1.2.2 Receiver parameters

8.1.2.2.1 Receiver Spurious Emissions

IEEE Std. 802.11 [i.10] equipment has to comply with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8] and which are based on ERC Recommendation 74-01 [i.18].

8.1.2.2.2 Receiver Blocking

IEEE Std. 802.11 [i.10] equipment is Adaptive equipment intended to operate at an output power above 10 mW and therefore will have to comply with the Receiver Blocking requirements defined for Category 1 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.1.2.3 Antenna information

The typical antenna gain for IEEE Std. 802.11 [i.10] devices is assumed to be within the range from -2 dBi to 3 dBi for client devices and within the range 1 dBi to 4 dBi for Access Points. The majority of the antennas will have a omnidirectional radiation pattern. The use of beamforming techniques will result in additional antenna gain however the limit on the total e.i.r.p. will have to be respected.

Some Access Points are equipped with higher gain antennas to serve specific use cases where a directional antenna beam is required.

8.1.3 Market information

The first version of the IEEE Std. 802.11 [i.10] protocol was released in 1997. The technology became really successful with the release of IEEE 802.11b-1999 [i.38] in 1999 that covered data rates up to 11 Mbps. Billions of IEEE Std. 802.11 [i.10] devices have shipped over the past 20 years and there is no sign of slowing down. On the contrary, according to a new market data report from global tech market advisory firm, ABI Research [i.44], more than 20 billion Wi-Fi devices are forecasted to ship between 2019 and 2024.

Not many people twenty years ago would have predicted the enormous impact of wireless networking in unlicensed spectrum. This impact is best demonstrated by Wi-Fi, the most prominent of the technologies that utilize unlicensed spectrum. According to the Wi-Fi Alliance® "Wi-Fi CERTIFIED now includes over 50 000 products ranging from advanced access points and smartphones, to laptops TVs, and gaming computers, as well as Internet of Things (IoT) devices such as smart thermostats, door locks, and even hot water heaters." Every enterprise business category utilizes Wi-Fi to produce output, from agriculture to manufacturing to transportation and more. Every school or university uses Wi-Fi to provide internet access to students and teachers. Wi-Fi is now available in most public places. Wi-Fi has become so successful that over half of all Internet traffic in Europe begins or ends on a Wi-Fi Network. In Western Europe, public hotspots are expected to grow by 20 % per year, on average, through 2023, and Wi-Fi speeds will increase also to an average of 97,4 Mbps, according to Cisco's recently released Internet Report. In addition, the economic impact from Wi-Fi is large, globally projected to reach nearly €3,25 trillion per annum by 2023, according to a report commissioned by the Wi-Fi Alliance [i.42].

Most IEEE Std. 802.11 [i.10] devices that ship today are dual band (2,4 GHz and 5 GHz) and additional spectrum is expected to become available in the 6 GHz range in 2020. However, the 2,4 GHz band will always remain of extreme importance for the Wi-Fi technology. It is the only band where no incumbent services such as radars or fixed services need protection.

8.1.4 Challenges (IEEE 802.11)

8.1.4.1 Introduction

The current rules for the operation of both Non-Specific SRDs and Wideband Data Transmission Systems in the 2,4 GHz band in Europe have proved to be well aligned with the objective of efficient spectrum sharing, as required by the European Commission.

The main difference between the rules for Non-Specific SRDs and those for Wideband Data Transmission Systems is the transmit power limit. Non-Specific SRDs are restricted to 10 mW while Wideband Data Transmission Systems are allowed to transmit at up to 100 mW.

Starting from ETSI EN 300 328 (V1.7.1) [i.6], the use of a Medium Access mechanism was required. This Medium Access mechanism together with the Power Spectral Density requirement for non-hoppers form the main distinction between requirements for the 100 mW Wideband Data Transmission Systems and the requirements for the 10 mW Non-Specific SRDs. As the Medium Access mechanism was not further specified and no test method was included in the standard, TCAM instructed ETSI in June 2008 to detail the requirements of a Medium Access mechanism in a revision of ETSI EN 300 328 (V1.7.1) [i.6].

8.1.4.2 Effective spectrum sharing in the 2,4 GHz band

As described in clause 5.1.1, Annex 3 of ERC Recommendation 70-03 [i.1] mandates the use of an Adequate spectrum sharing mechanism such as LBT or DAA.

While many Wi-Fi devices operate in the 5 GHz band today, almost all Wi-Fi devices are also capable of operating in the 2,4 GHz band. Wi-Fi's success, starting twenty years ago, is based on the application of the LBT spectrum sharing mechanisms in the 2,4 GHz band that had been developed by the IEEE 802.11 working group, with the lessons learnt in the 2,4 GHz band used to guide the specifications of similar spectrum sharing mechanisms in the 5 GHz band (and soon the 6 GHz band).

ETSI EN 300 328 (V2.2.2) [i.8] specifies two Adaptivity mechanisms based on spectrum sensing: Listen Before Talk (LBT) and Detect And Avoid (DAA). The key principle of both is that a device should not transmit in a channel unless the channel is considered free. This has allowed unlicensed spectrum to be shared by Wi-Fi and other adaptive technologies so effectively for so many years.

Adaptivity as currently described in ETSI EN 300 328 (V2.2.2) [i.8] meets the desire of the European Commission for efficient and shared use of spectrum. This desire is documented by the Commission Implementing decision of 4 August 2015 [i.39] containing the standardization mandate to CENELEC and ETSI for standards to be developed under the Directive 2014/53/EU [i.17]. It defines in Annex II, point 3 the 'Essential Requirements that need to be covered by the standardisation work". Paragraph (3) contains the following:

> *Moreover, the development of sharing mechanisms and mitigation techniques should be a constant priority in order to achieve the efficient use of radio spectrum, in line with the electronic communication regulatory framework including the Radio Spectrum Policy Programme (RSPP), considering the need to increase sharing capabilities of equipment.*

Equal access has been defined by the EC in document TCAM(26)44. The IEEE Std. 802.11 community is afraid that unless a homogeneous mechanism to implement equality is defined, it is likely that equality will not be achieved in many use cases.

8.1.4.3 The future of the 2,4 GHz is a risk for IEEE Std. 802.11

8.1.4.3.1 Introduction

The challenges that could adversely affect spectrum sharing for Wideband Data Transmission Systems, particularly for Wi-Fi systems (based on IEEE Std. 802.11 [i.10]), are summarized below:

- A possible relaxation or removal of the Power Spectral Density (PSD) requirement for non-FHSS devices
- A possible relaxation for FHSS devices
- Increased usage by non-adaptive systems using the Medium Utilization (MU) mechanism

8.1.4.3.2 The risk of removing the Power Spectral Density requirement for non-FHSS

A potential challenge for Wi-Fi, and the continued effective sharing of the 2,4 GHz band, are recent proposals to re-consider the rules in the 2,4 GHz band, particularly in relation to PSD limits for Wideband Data Transmission Systems.

Wi-Fi is an example of a technology operating in the 2,4 GHz band that is regulated in Europe as a Wideband Data Transmission System, as defined by Annex 3 of ERC Recommendation70-03 [i.1]. This annex specifies a power limit of 100 mW e.i.r.p., conditioned on a PSD limit of 10 mW/MHz e.i.r.p. and the use of a polite sharing mechanism. Technologies operating in the 2,4 GHz band which cannot meet the PSD requirement specified for Annex 3 have to use Annex 1 of ERC Recommendation70-03 [i.1] and therefore their output power is limited to 10 mW e.i.r.p.

A proposal has been made to the SRD/MG to relax or remove the PSD limit of 10 mW/MHz e.i.r.p. for Wideband Data Transmission Systems. The effect of accepting these proposals would be to allow narrowband devices to operate as Wideband Data Transmission Systems using a transmit power of up to100 mW e.i.r.p. in a narrow bandwidth of one or a few MHz. The main examples of such devices are those based on the Bluetooth BLE specification and on the IEEE 802.15.4 technology standard. Concerns were expressed that this proposal is in conflict with the way the Commission Decision 2006/771/EC [i.2] has defined Wideband data transmission devices (see clause 5.2). According to this Decision, *Wideband Data Transmission Devices covers devices that use wideband modulation techniques to access spectrum*. A more serious problem is that the use of narrow band and wide band systems with asymmetric PSDs but similar transmit power risks the efficacy of the current Adaptivity mechanisms that has enabled such effective spectrum sharing of the 2,4 GHz band for so many years.

8.1.4.3.3 The risk of relaxing the rules for FHSS devices

The main difference between the requirements for FHSS devices and non-FHSS devices is that the Power Spectral Density requirement does not apply to FHSS devices.

Over the past years, ERM TG11 received several proposals to modify the equipment categorization in ETSI EN 300 328 (V2.2.2) [i.8] so that manufacturers could qualify their devices as FHSS devices and as such the PSD requirement would not apply. Some proposals were implemented, others were not implemented. The current standard does not force an FHSS system to transmit on all (i.e. the minimum required number of) Hopping Positions but if it does not it will still be counted as if the device was transmitting on the unused hopping positions to prevent this is used to avoid the PSD requirement.

8.1.4.3.4 Use of the MU mechanism should be further discouraged

An additional challenge for Wi-Fi, and the continued effective sharing of the 2,4 GHz band, is related to the possibility that increased numbers of non-adaptive devices make use of the MU mechanism.

ETSI EN 300 328 (V2.2.2) [i.8] allows a non-adaptive device using the MU mechanism to transmit at full power in the 2,4 GHz band for up to ten percent of the time without sensing the state of the channel. This approach conflicts with the Adaptivity principles that promote polite medium access, and which have been a substantial driver of the success of the 2,4 GHz band for the last twenty years.

According to some members of the IEEE 80211 community participating in ERM-TG11, there is a risk that more systems will use the MU approach in the future as a way of obtaining access to the channel without sensing the availability of that channel, particularly if the PSD requirement is relaxed or removed. The problem is that several MU systems, each transmitting blindly for up to ten percent of the time, will cause LBT systems to rarely gain access to the medium. This would significantly reduce the effectiveness of the 2,4 GHz band as a platform for socio-economic development in Europe.

According to some members of the IEEE 80211 community participating in ERM-TG11, the current MU approach needs to be re-considered to prevent that the adaptivity mechanism in polite systems could be permanently triggered by (impolite) non-adaptive systems.

8.1.5 Relationship between the IEEE 802.11 technology and ETSI EN 300 328

8.1.5.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.1.5.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☐

Non-Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU) < 10 %: ☐

P_{out} (e.i.r.p.): ….. dBm

DC: ….. %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.1.5.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☒

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☐

Medium Utilization (MU) < 10 %: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): ….. dBm

DC: ….. %

Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.1.5.1.3 Receiver category

Receiver category 1: ☒

Receiver category 2: ☐

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☐

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☐

Receiver category 3: ☐

Non-adaptive equipment with MU ≤ 1 %: ☐

Adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm (e.i.r.p.): ☐

8.2 Bluetooth® wireless technology

8.2.1 Introduction and main characteristics

8.2.1.0 Introduction

Bluetooth® wireless technology was originally conceived as a robust wireless technology standard for exchanging data over short distances and for establishing Personal Area Networks (PANs) as an alternative to RS-232 data cables but has since then diverged into a wide range of applications and additional topologies like point-to-multipoint and mesh, and that has enabled broader development in additional verticals such as industrial, commercial, and home automation. Bluetooth is now established on a global scale, e.g. smartphones, computer peripherals, automotive and hearing aids, as well as utilities and IoT.

Today, Bluetooth is shipped with all (100 %) smartphones, tablets and laptops; this represents a total of over 2 billion devices annually. According to the Bluetooth SIG 2019 Marketing Update, the volume of Bluetooth units globally installed is in the range of 13 billion devices with annual shipments estimated to 4 billion. Audio and data applications account for about 1 billion devices each. In the period 2018 to 2023 annual shipments are predicted to have a Compound Annual Growth Rate, CAGR of 8 % and reach 5,2 billion in 2023 (Source: ABI Research, 2019) when 90 % of them will include LE.

There are two types of Bluetooth systems: Basic Rate/Enhanced Data Rate (BR/EDR) and Low Energy (LE), and each of them has a separate set of PHY options. Both systems include device discovery, connection establishment, and connection mechanisms. Devices are either dual-mode systems (BR/EDR & LE) that implement both systems or are or single-mode BR/EDR or single-mode LE systems.

The Bluetooth standard is managed within the Bluetooth Special Interest Group (SIG), which has more than 35 000 member companies in the areas of telecommunication, computing, networking, and consumer electronics. At one point, the IEEE standardized Bluetooth as IEEE 802.15.1 [i.40]; however, that was discontinued in 2005.

The Bluetooth SIG oversees the development of the Bluetooth specification, manages the qualification program, and protects the trademarks. The Bluetooth SIG has developed a broad portfolio of specifications (profiles, services, and models) intended to cater to a growing set of use cases which include solutions for wireless audio, mesh, data transfer, location services or device networks and many other usages.

A manufacturer demonstrates compliance with the Bluetooth specification via the Bluetooth qualification program to sell its device as a Bluetooth device. A portfolio of patents applies to the technology, which is licensed to individual qualified devices and product designs after the conclusion of qualification testing and declarations. At this point (Q2 2020), about 5 000 product qualifications are done annually.

8.2.1.1 Basic Rate (BR) and Enhanced Data Rate (EDR)

BR was the original Bluetooth system which defined a frequency hopping scheme optimized for sharing the available spectrum among several piconets, i.e. small networks of devices sharing the same hopping pattern. The hopping scheme is based on a hop rate of 1 600 hops per second which gives a Bluetooth slot duration of 625 µs.

The Central device coordinates the hop patterns within a piconet. A device can participate in multiple piconets and can be Central in one and Peripheral in another, or Peripheral in multiple piconets (these are known as scatternets). A Central device can also broadcast data to one or more Peripheral devices in a piconet.

For improved co-existence with other technologies, Bluetooth has included adaptive frequency hopping (AFH) since v.1.2 from 2003.

The BR system was extended to include an optional Enhanced Data Rate (EDR) system as well as Alternate Mac-Phy (AMP) layer extensions. The Basic Rate system offers synchronous and asynchronous connections with a data rate of 1 Mb/s for Basic Rate using GFSK, 2 Mb/s for EDR using π/4-DQPSK (EDR2) and 3 Mb/s for EDR using 8DPSK (EDR3) and high-speed operation up to 54 Mb/s with the 802.11 AMP.

In the BR/EDR system, the available spectrum is divided into 79 physical channels, separated by 1 MHz. The BR/EDR system supports a transmit power control mechanism which allows a device to request an incremental change (increase or decrease) in the transmit power level of the remote device.

8.2.1.2 Low Energy (LE)

8.2.1.2.0 Background information

LE was added to the Bluetooth specification in 2010 with the v.4.0 release [i.31]. The LE system was originally designed to enable products that exhibited lower current consumption, lower complexity and lower cost than BR/EDR devices. The LE system was also designed for use cases and applications with lower data rates and lower duty cycles than BR/EDR devices.

In the LE system, the available spectrum is divided into 40 physical channels, separated by 2 MHz, where three channels are Primary Advertising channels that are used by advertising devices to make their presence known to scanning devices. The 37 other channels are used as general-purpose channels for point-to-point connections between devices (either asynchronous or isochronous), for connectionless communication between devices, and as Secondary Advertising channels.

Like BR/EDR, the LE system also supports piconets and scatternets.

The LE system supports a transmit power control mechanism which allows a device to request an incremental change (increase or decrease) in the transmit power level of the remote device. There is also a mechanism where a device can request the remote device to change to the maximum transmit power level.

The LE system has two modulation schemes, both based on GFSK and supporting 1 Msym/s and 2 Msym/s where

a) the mandatory 1 Msym/s modulation scheme supports two PHYs:

  - LE 1M, with uncoded data at 1 Mb/s.

- LE Coded, with coded date at either 125 kb/s (LE 125 k) or 500 kb/s (LE 500 k).
- An LE device supports the LE 1M PHY while support for the LE Coded PHY is optional.

b) the optional 2 Msym/s modulation supports a single PHY; LE 2M, with uncoded data at 2 Mb/s.

Following the introduction in 2010, the system has undergone extensions and improvements through Bluetooth v4.1 [i.30], Bluetooth v4.2 [i.29], Bluetooth v5.0 [i.28], Bluetooth v5.1 [i.27], Bluetooth v5.2 [i.26]. Each update to the system has added capabilities and improvements in security, topology, coexistence, direction finding, mesh, and audio. At this point (Q2 2020), new devices may be qualified to Bluetooth v4.2 [i.29], Bluetooth v5.0 [i.28], Bluetooth v5.1 [i.27] or Bluetooth v5.2 [i.26], prior versions are no longer qualifiable. Further advancements in the Bluetooth specifications and functionality are to be expected but cannot be described at this point in time.

Bluetooth v5.0 [i.28] added extended Advertising mode which increased the broadcast capacity in one Advertising Protocol Data Unit (PDU) by about 8x and which enabled advertising on all 40 physical channels. This version also introduced a new frequency hopping algorithm to improve the statistical use of available channels when some channels are mapped out of the channel map when a device adapts to local interference conditions, as in BR/EDR. There is also a provision for device to request a specific minimum number of channels in the map, which may be used to maintain a minimum set of hopping channels.

The mesh mode was added to provide extended coverage in a dense network with short latency application requirements.

Bluetooth v5.1 [i.27] added direction-finding capabilities using Angle of Arrival (AoA) and Angle of Departure (AoD) calculations. It allows devices to make their direction available for peer devices by transmitting direction-finding enabled packets. The transmitter and the receiver could use a single antenna or an antenna array.

Bluetooth v5.2 [i.26] added isochronous transports which allow devices connected using an asynchronous connection to establish one or more isochronous connections with each other. The isochronous connection can be used to transfer isochronous data (which is inherently time-bound). A device can also broadcast isochronous data using isochronous connectionless transports.

The improvements relative to the earlier releases of the Bluetooth specification illustrate the impact of the use of intelligence in the lower layers of the device architecture, where more features facilitate shared spectrum use and fast response to changing conditions.

8.2.1.2.1 LE Advertising Channels and Events

The LE system employs, like its BR/EDR predecessors, a frequency hopping mechanism to combat interference and access the shared medium. Additionally, LE PDU transmissions occur in defined timing slots called events, thus time multiplexing transmitting devices transmitting and responding devices.

In this regard, an LE device can occupy two different operating modes: advertising mode and connection mode.

The connection mode is used in peer-to-peer communication between two peers (referred to as Central and Peripheral for connection-oriented communication, and referred to as Broadcast and Observer for connectionless communication, with devices hopping among the 37 data channels.

In Advertising mode, PDU transmissions occur in Advertising Events where the PDUs are transmitted on up to three Primary Advertising channels (2 402 MHz, 2 426 MHz and 2 480 MHz), or the 37 Secondary Advertising channels (which are the same as the channels in connection-oriented communication mode).

Devices can use the advertising mode to initiate a connection, solicit a response from another device, or to broadcast information (periodically or aperiodically).

There are two advertising schemes: legacy advertising and extended advertising:

1) Legacy advertising always uses the Primary Advertising channels, and can operate with a configurable packet length and configurable low duty cycle or a configurable high duty cycle (reserved for connectable packets only).

2) Extended advertising always uses the configurable low duty cycle and a fixed packet length.

Figure 4 illustrates the Primary Advertising (in red) and Secondary Advertising (in blue) channels, and how they map onto the 2,4 GHz spectrum with respect to Wi-Fi.

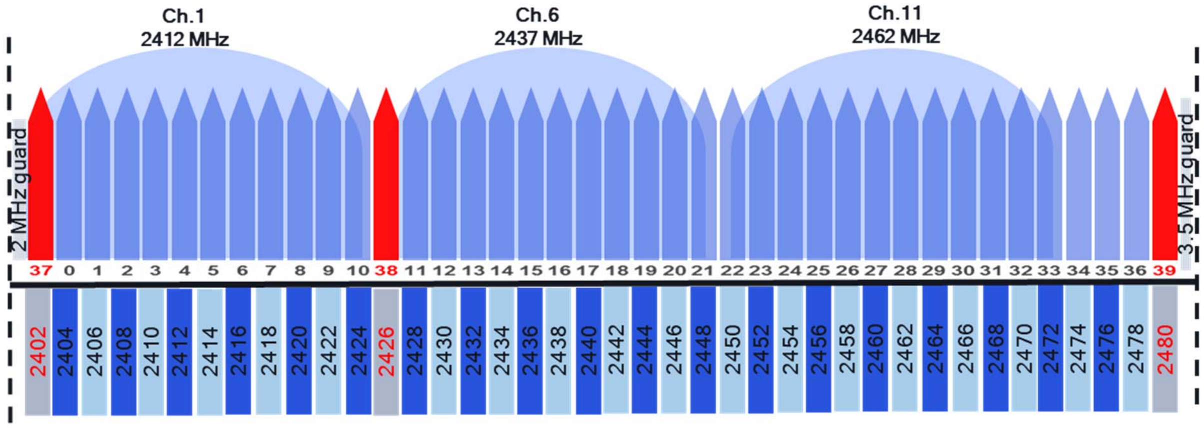

Figure 4: LE channel map

The Primary Advertising channels play a key role in LE operation. Examples of this are procedures to initiate a connection, or to exchange information between two devices before pairing. Before switching to the Secondary Advertising channels used to carry periodic or aperiodic data, LE devices first use the Primary Advertising channels to communicate the physical parameters and the timing schedule of the Secondary Advertising PDUs.

In addition, applications for asset tracking, indoor positioning and location finding, employ standalone advertising events on the Primary Advertising channels.

8.2.1.2.2 Maximum and typical LE advertising durations

Figure 5 illustrates the hopping sequencing used on the Primary Advertising channels, where the device switches channels during the advertising event (the start of consecutive advertising events are separate by the Advertising Interval). The advertising PDU may change at the next event, and an event may end at any time (before the transmission on three channels).

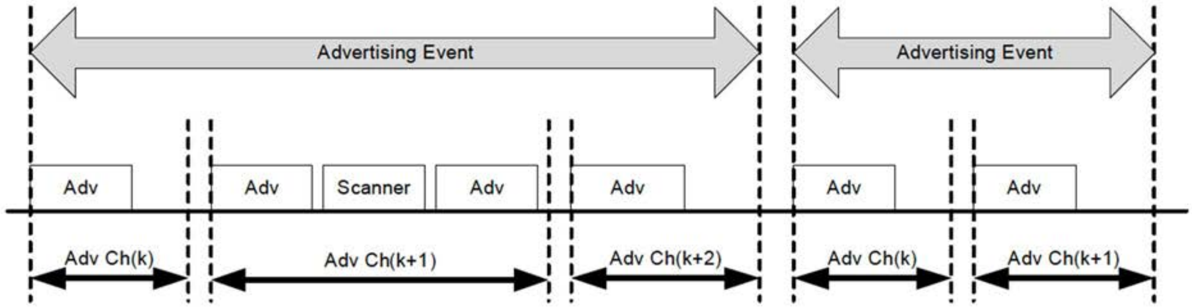

Figure 5: Hopping sequencing scheme of the primary advertising channels

The maximum packet length (and corresponding maximum packet transmission time) varies depending on the type of advertising scheme used (legacy or extended) and on the packet type being used (fixed or variable length) and on the PHY used (1 M Uncoded (1 Mb/s), S = 2 Coded (500 kb/s), or S = 8 Coded (125 kb/s)).

Advertising events on primary advertising channels typically have a low duty cycle:

1) The Advertising Interval between advertising events for low duty cycles for legacy or extended advertising varies between 20 ms and 10 486 ms. A random delay (advDelay) between 0 and 10 ms is added between all low duty cycle legacy and extended advertising events on the Primary Advertising channels, to minimize collision over the air. In effect, this adds an average 5 ms to the Advertising Interval.

2) The Advertising Interval between events for high duty cycle connectable (legacy) advertising is 3,75 ms maximum

While clause 8.2.1.2.3 discusses the max duty cycle for the different advertising types, it should be noted that the typical duty cycle is highly dependent on application requirements.

The Duty Cycle (in %) for each advertising channel can be calculated thus:

[Packet_Tx_Time (ms) / Advertising_Interval (ms)] × 100.

Real-time asset tracking or indoor location reports a change of state or location quickly, and therefore their duty cycle can show peaks of their transmission cycle close to the maximum duty cycle. When the advertising interval is 100 ms, the duty cycle is ~0,38 % with Legacy Advertising. In other use cases, like sensor networks, it is significantly lower. For instance, for an environmental sensor normally reporting data every 5 minutes, the average duty cycle is ~0,13 %.

8.2.1.2.3 Durations and Duty Cycles in LE Advertising

LE Advertising includes the different advertising PDU types in the following figure, which outlines the respective advertising PDUs and the resulting PDU transmission time (TxTime) at the Max Length possible for that PDU, advertising scheme, and PHY combination.

Table 7: LE advertising packets and TxTime at Max Length

PACKET TYPE	**ADVERTISING SCHEME**			**PHYSCIAL LAYER**			**Tx Time (us)**
	Legacy		**Extended**	**1 M Uncoded**	**S = 2 Coded**	**S = 8 Coded**	
	Low duty	High duty	Low Duty	1 Mbps	500 kbps	125 kbps	
ADV_IND (NS_C_U)	•			•			376
ADV_DIRECT_IND (NS_C_D)	•			•			176
ADV_DIRECT_IND (NS_C_D)		•		•			176
ADV_NONCONN_IND (NS_NC_U)	•			•			376
ADV_SCAN_IND (S_U)	•			•			376
SCAN_REQ	•			•			176
SCAN_RSP	•			•			376
ADV_EXT_IND (NS_NC_U_NA)			•	•			128
ADV_EXT_IND (NS_NC_U_NA)			•		•		606
ADV_EXT_IND (NS_NC_U_NA)			•			•	1 296
ADV_EXT_IND (NS_NC_U_A)			•	•			168
ADV_EXT_IND (NS_NC_U_A)			•		•		576
ADV_EXT_IND (NS_NC_U_A)			•			•	1 168
ADV_EXT_IND (NS_NC_D_NA)			•	•			176
ADV_EXT_IND (NS_NC_D_NA)			•		•		702
ADV_EXT_IND (NS_NC_D_NA)			•			•	1 680
ADV_EXT_IND (NS_NC_D_A)			•	•			216
ADV_EXT_IND (NS_NC_D_A)			•		•		576
ADV_EXT_IND (NS_NC_D_A)			•			•	1 296
ADV_EXT_IND (C_U)			•	•			120
ADV_EXT_IND (C_U)			•		•		576
ADV_EXT_IND (C_U)			•			•	1 296
ADV_EXT_IND (C_D)			•	•			120
ADV_EXT_IND (C_D)			•		•		576
ADV_EXT_IND (C_D)			•			•	1 296
ADV_EXT_IND (S_U)			•	•			120
ADV_EXT_IND (S_U)			•		•		576
ADV_EXT_IND (S_U)			•			•	1 296
ADV_EXT_IND (S_D)			•	•			120
ADV_EXT_IND (S_D)			•		•		576
ADV_EXT_IND (S_D)			•			•	1 296

NS = Non-scannable (scan request not allowed), S = scannable (scan request allowed), NC = Non-connectable (connect request not allowed)
C = Connectable (connect request allowed), U = Undirected (not directed to a specific device), D = directed (to a specific device)
NA = No auxiliary packet on secondary advertising channels (extended advertising only)
A = Auxiliary packet on secondary advertising channels (extended advertising only)

The maximum duty cycle can be computed with the maximal length of advertising data, the minimum Advertising_Interval + average Advertising delay (20 ms + 5 ms). If the observation window is less than two advertising events long, the AdvDelay factor could not be taken into account as there would be no second advertising event.

Undirected connectable legacy advertising ADV_IND as an example, and using an AdvDelay of 5 ms, the max duty cycle is: 376 μs in 25 ms = 1,5 % per channel.

The plots provided in figure 6 to figure 8 use the worst-case scenarios for legacy and extended advertising using the Primary Advertising channels (maximum packet length, minimum advertising interval and zero advDelay. It should be noted that an advDelay of zero is only possible when observing a single advertising event, and would not occur in real-life operation when two or more advertising events are used).

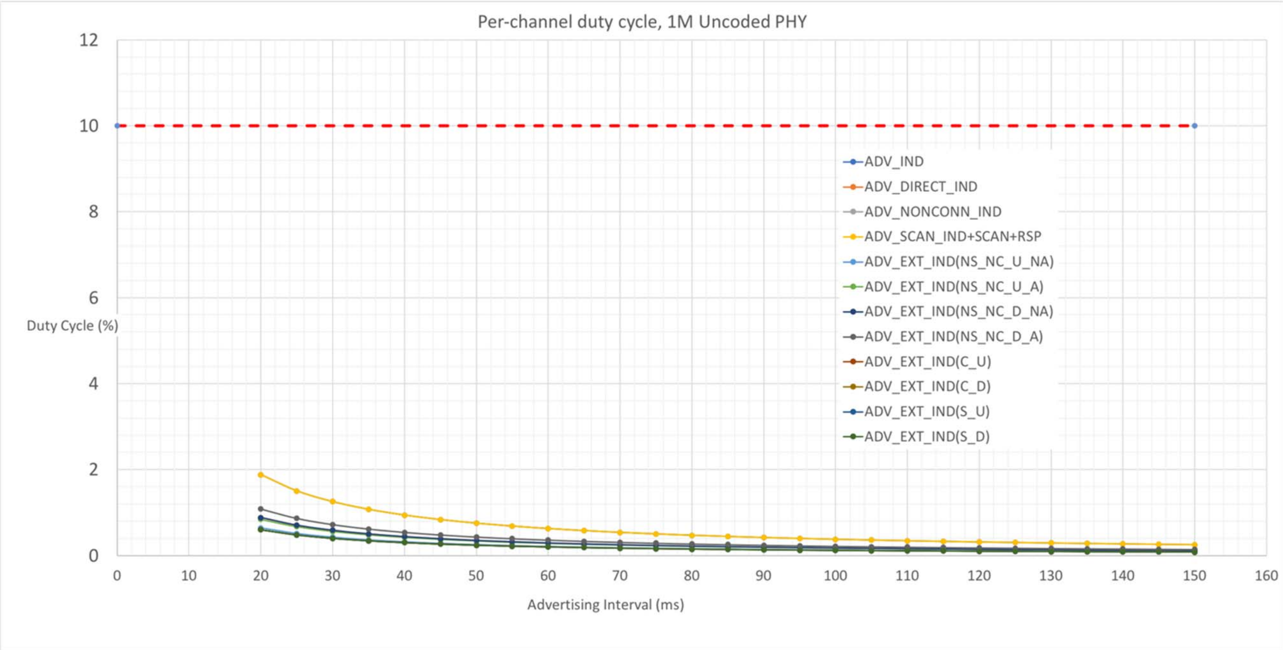

Figure 6: Per channel duty cycles by PDU type for LE legacy and extended advertising, 1 M Uncoded PHY

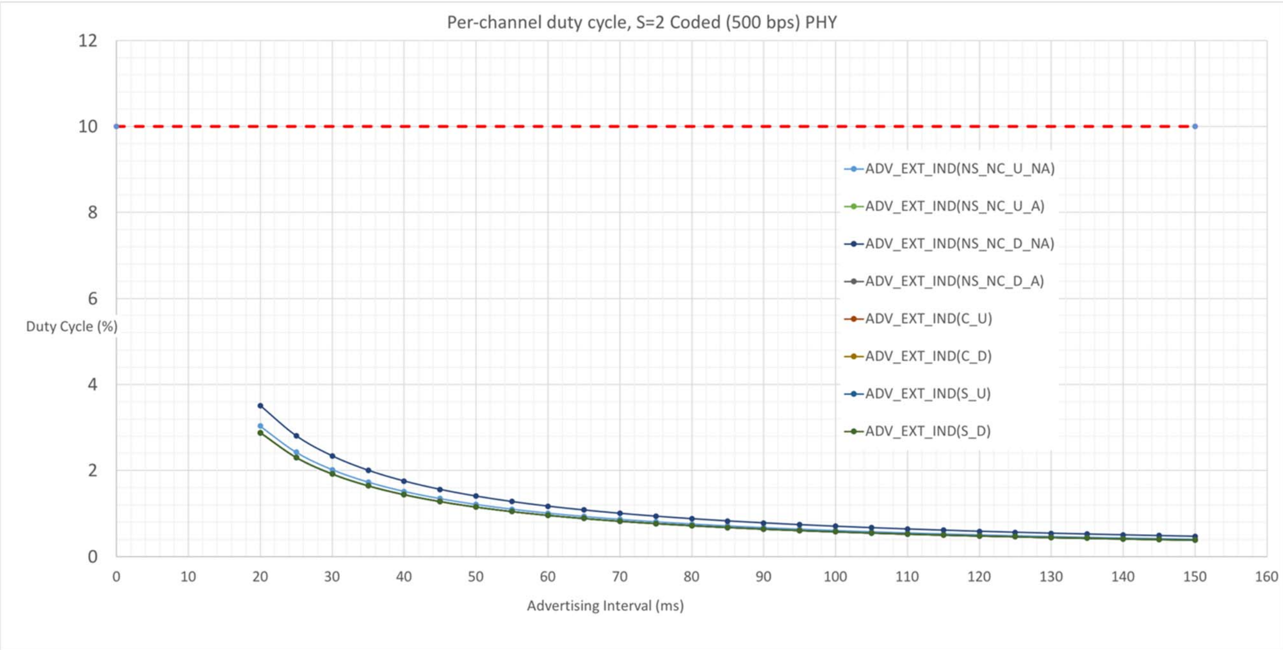

Figure 7: Per channel duty cycles by PDU type LE legacy and extended advertising, LE 500 k

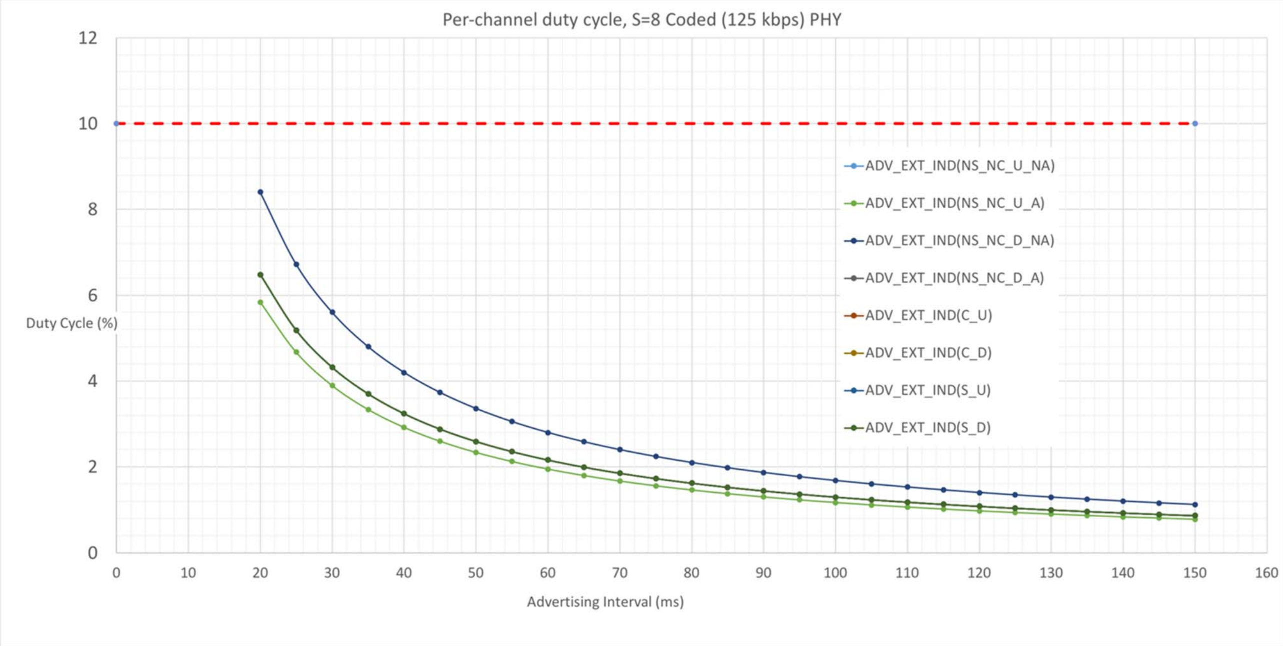

Figure 8: Per channel duty cycles by PDU type for LE legacy and extended advertising, LE 125 k

From the above, irrespective of the PDU type in use, the length of the Advertising Interval, the length of the PDU, and the PHY on which the PDU is transmitted, it can be seen that legacy and extended advertising PDUs always remain under 10 % duty cycle per advertising channel.

The real-world duty cycle figures would be lower still because an AdvDelay of average 5 ms would be observed, in effect lengthening the Advertising Interval and thus the time between subsequent transmissions on any given advertising channel.

8.2.1.3 Bluetooth Mesh

Bluetooth mesh is a full-stack wireless mesh technology specified by Bluetooth SIG that defines interoperable communication protocols covering all OSI layers from the PHY to the application layer.

Bluetooth mesh is designed for high-density IoT connectivity applications that use messages with small payloads, require low-latency multicast communication, and extended coverage. The Bluetooth mesh protocol is a managed flooding protocol in which nodes relay messages sent on Advertising Channels. Up to 127 hops over intermediate relay nodes are supported. Message caching is used to prevent relaying messages recently seen: every relay node filters packets that are not for the network it is a part of, and further filters recently received packets, to prevent unnecessary retransmissions.

Maximum useful payload is 11 octets for unsegmented messages and 380 octets for segmented messages.

Scalability of a Bluetooth mesh network is defined by:

- The 15-bit unicast address space (up to 32 767 nodes per network).
- Message collisions resulting from unscheduled overlapping radio transmissions (statistically at 200 messages/s the probability of collisions raises above 10 %). Burst message transmission is allowed, however there is a recommendation to not originate 100 or more messages in a moving 10-second window.
- A node may be a member of multiple networks and multiple subnets within a network.

Security in Bluetooth mesh is mandatory, with the provisioning protocol supporting strong device authentication and generation of high entropy keys. Dual-layer security includes transport security/authentication of messages and application security enforcement of access rights. The key refresh procedure supports identification and measures to combat potentially compromised nodes.

8.2.2 Technical Description

8.2.2.1 Transmitter Parameters

8.2.2.1.1 Transmitter RF output power

Depending on the application and use case, the transmitter RF output power of a Bluetooth device can range from lower than 0,01 mW e.i.r.p. up to the regulatory limit of 100 mW e.i.r.p.

Implementations serving typical "personal" use cases generally operate at the lower RF power levels while for example, the IoT and industrial applications may go up to the 100 mW e.i.r.p. level.

The Bluetooth specification identifies devices into power classes based on their highest output power capabilities according to table 8 and table 9.

Table 8: BR/EDR power classes

Power Class	Maximum Output Power (Pmax)	Minimum Output Power (see note)
1	100 mW (+20 dBm)	1 mW (0 dBm)
2	2,5 mW (+4 dBm)	0,25 mW (-6 dBm)
3	1 mW (0 dBm)	(not explicit)
NOTE: Minimum output power at maximum power setting.		

The BR/EDR system specified a transmitter performance and power control enabling up to 100 mW e.i.r.p. from the start. It supports a transmit power control mechanism which allows a device to request an incremental change (increase or decrease) in the transmit power level of the remote device. There is also a mechanism where a device can request the remote device to change to the maximum transmit power level.

Table 9: LE Power classes

Power Class	Maximum Output Power (Pmax)	Minimum Output Power (see note)
1	100 mW (+20 dBm)	10 mW (+10 dBm)
1,5	10 mW (+10 dBm)	0,01 mW (-20 dBm)
2	2,5 mW (+4 dBm)	0,01 mW (-20 dBm)
3	1 mW (0 dBm)	0,01 mW (-20 dBm)
NOTE: Minimum output power at maximum power setting.		

LE modes were initially introduced with a maximum RF output power of 10 mW e.i.r.p., but with Bluetooth 5.0 [i.28] in 2016, it also was enabled up to 100 mW e.i.r.p. The LE system includes a transmit power control mechanism like its predecessor. It also allows devices to autonomously change their local transmit power levels and inform the remote device that such a change has occurred.

Until now, the deployed volumes of devices operating at the lower power level far exceed the volumes of devices operating at power levels above 10 mW e.i.r.p. This is however subject to change because of increased momentum in newer verticals but also as the combination of customer expectations for longer range and more efficient radio architectures that enable higher RF power levels in well-established use cases.

Bluetooth is designed to support a wide range of achievable ranges between two devices (see "Understanding Bluetooth Range" [i.43] from Bluetooth SIG) in a point to point connection. The actual range obtained in a practice depends on many factors, including the PHY type used, the power level of the transmitter, the distance between the devices, the transmission pathloss and the level of background interference.

Note that Bluetooth mesh provides the additional means to extended coverage vastly beyond the figures obtained with this tool.

8.2.2.1.2 Occupied Channel Bandwidth

Bluetooth equipment operating in the BR mode has an Occupied Channel Bandwidth of about 1 MHz. When operating in the EDR modes the Occupied Channel Bandwidth is about 1,2 MHz.

In LE mode the Occupied Channel Bandwidth is about 1,2 MHz for LE 1M, LE 500 k, and LE 125 k, while it is about 2 MHz for LE 2 M operation.

8.2.2.1.3 Spectrum Sharing and Medium Usage

From the very beginning, Bluetooth has met the requirements to be considered a frequency hopper. Nominally each piconet had its pseudorandom hopping sequence of 79 hops.

With the increasing market penetration of 802.11/Wi-Fi, adaptive frequency hopping was added to the standard in v.1.2 (2003). Using the feature, frequencies found to be occupied are removed from the hop sequence of the affected piconet.

The introduction of the LE system meant that channel spacing increased from 1 MHz to 2 MHz and reduced the hop sequence accordingly from 79 hops to 40 hops.

Both the BR and the LE system have guard bands at the lower end (2 MHz) and the upper end (3,5 MHz) of the band.

In order to avoid interference between co-located Bluetooth and mobile wireless systems (MWS) or IEEE Std. 802.11 [i.10] radios, the Bluetooth specification provides medium access arbitration function, This is a feature whereby two devices indicate to each other which time slots that are available for transmission and reception. A slot could be unavailable because of external conditions (e.g. MWS coexistence) or internal conditions (e.g. scatternet commitments). The arbitration function protects the Bluetooth radio and the other radios from mutual interference, thus maximizing the usability of the Bluetooth radio. This is an example of an industry developed spectrum sharing feature that is not called for in regulation.

8.2.2.1.4 Duty Cycle

The duty cycle of a Bluetooth device varies with application and use cases, it can range from 0,1 % to 1 % in, for example, IoT applications, up to the theoretical maximum which is about 85 % in BR/EDR and LE systems.

8.2.2.1.5 Adaptivity

The Bluetooth specification provides the means for adaptive frequency hopping in both connected and connectionless modes, through channel map updates communicated via peers in the different network topologies, where the adapted hopping frequency has similar statistical properties as the nominal hopping sequence. Adaptive Frequency Hopping utilizes metrics obtained through active or passive channel assessment or a combination of the two methods, or through data supplied by the Host, or reports by the Peripheral or from other hardware coexistence interfaces. These modes of adaptive medium access allow Bluetooth to share spectrum with other systems like Wi-Fi but they are not supported by ETSI EN 300 328.

The BR/EDR system supports a Channel Quality Driven Data Rate (CQDDR) change mechanism, which allows a receiver to dynamically control the packet type transmitted by the remote device to optimize the data throughput. The receiver can indicate its preferred coding, packet size and rate (BR, EDR2 or EDR3) to use the best link parameters for efficient use of the available bandwidth and minimize retransmissions.

Similarly, the LE system supports PHY and Data Length Update procedures which allow devices to pick the best PHY (LE 1 M, LE 2 M, LE 500 k and LE 125 k) and the optimal packet length to make the best use of the available bandwidth.

8.2.2.1.6 Transmitter Unwanted Emissions

Implementations that carry the Bluetooth trademark complies with international regulations identified in the Bluetooth specification.

8.2.2.2 Receiver Parameters

8.2.2.2.1 Receiver Sensitivity

The specification of BR defines receiver sensitivity of ≤ -70 dBm at a BER of 0,1 %. In the case of EDR receiver sensitivity is ≤ -70 dBm at a BER of 0,01 %.

With a BER-percentage, which is a function of the supported payload length, where the payload can be any length from 1 to 255 bytes, the LE specification defines receiver sensitivity according to the following:

- LE 1 M and LE 2 M: ≤ -70 dBm
- LE 500 k: ≤ -75 dBm
- LE 125 k ≤ -82 dBm

The signal impairments are defined in the Bluetooth qualifications test procedure and include variations in the carrier frequency offset, carrier frequency drift, modulation index, and symbol timing drift.

8.2.2.2.2 Receiver Selectivity

The BR/EDR system defines receiver selectivity where the BER is ≤ 0,1 % for wanted signal input to the receiver at -67 dBm while an interfering signal is present at several specified distances from the operating frequency as given in table 10.

Table 10: BR/EDR Receiver Selectivity

Interfering Signal Frequency	C/I [dB]
Co-channel	11
±1 MHz offset	0
±2 MHz offset	-30
±3 MHz offset	-40
Image frequency	-9
Image Frequency ± 1 MHz offset	-2

Similarly, the LE system defines receiver selectivity with the PER equivalent to BER of ≤ 0,1 % for wanted signal input to the receiver at -67 dBm while an interfering signal is present at several specified distances from the operating frequency as given in table 11.

Table 11: LE Receiver Selectivity

Interfering Signal Frequency	C/I [dB]		
	LE 1 M & LE 2 M	LE 125 k	LE 500 k
Co-channel	21	12	17
±1 MHz offset	15	6	11
±2 MHz offset	-17	-26	-21
±3 MHz offset	-27	-36	-31
Image frequency	-9	-18	-13
Image Frequency ± 1 MHz offset	-15	-24	-19

The Bluetooth qualification test procedures include tests of these requirements.

8.2.2.2.3 Receiver Blocking

The BR/EDR system defines receiver blocking performance where the BER is ≤ 0,1 % for the wanted signal input to the receiver at -67 dBm. Similarly, the LE system defines receiver blocking with the PER equivalent to BER of ≤ 0,1 % for the wanted signal input to the receiver at -67 dBm.

The requirements are set with an interfering signal present at several specified distances in the range from:

- 30 MHz to 2 000 MHz and 2 003 MHz to 2 399 MHz, as well as
- 2 484 MHz to 2 997 MHz and 3 000 MHz to 12,75 GHz

Where the interferer level varies from -10 dBm to -35 dBm depending on the distance from the operating frequency.

The Bluetooth qualification test procedures include tests of these requirements.

8.2.3 Market Information

According to the Bluetooth SIG 2019 Marketing Update the volume of Bluetooth units globally installed is in the range of 13 billion devices with annual shipments estimated to 4 billion, where audio and data applications account for about 1 billion devices each. In the period 2018 to 2023 annual shipments are predicted to have a Compound Annual Growth Rate, CAGR of 8 % and reach 5,2 billion in 2023 (Source: ABI Research, 2019) when 90 % of them will include LE.

With the introduction of LE in 2010, major growth for equipment sets using Bluetooth as communication technology in addition to the initial application sets took off on a larger scale than earlier. The addition of different LE PHYs and diversification in topologies via point-to-multipoint and mesh has created momentum and enabled new verticals such as industrial, commercial, and home automation. This has meant the addition of environmental sensors, switches, light bulbs and fixtures, shock and vibration sensors for factory automation, location tags for asset tracking and wayfinding to the rapidly growing product portfolio.

The primary vectors for growth are IoT applications and Bluetooth audio, where the growing applications areas predominantly rely on LE to match constraints in terms of power, size and cost that drive design choices.

Although BR/EDR was the first generation of Bluetooth, there are no signs of that going away soon; in 2019 2,7 billion dual-mode BR/EDR & LE shipped. Dual-mode device shipments are steadily growing while single-mode BR/EDR shipment is on a slight decline; in 2019 about 700 million devices were shipped and in the next 5 years an annual decline of -3 % is anticipated.

In 2019 the LE single-mode device shipments exceeded 500 million devices and in the next five years, annual shipments of devices in this segment are predicted to triple (annual growth rates close to 30 %).

The annual shipment of Bluetooth devices for the Smart Building segment is poised to grow by a factor of seven by 2023 and by more than 50 % in the Smart Home segment (Source: ABI Research, 2019). This growth is driven by the increasing demands from home- and building owners for energy conservation, emission reductions and physical security.

Further details are available at https://www.bluetooth.com/bluetooth-resources/2019-bluetooth-market-update [i.45].

8.2.4 Challenges

8.2.4.0 Introduction

Until now, the deployed volumes of devices operating at the lower RF power level far exceed the volumes of devices operating at power levels above 10 mW e.i.r.p. This is however subject to change because of increased momentum in newer verticals but also as the combination of customer expectations for longer range and more efficient radio architectures that enable higher RF power levels in well-established use cases.

Depending on operational specifics for LE Class 1 (100 mW) in Primary Advertising mode or Connected/Broadcast mode, the current version of ETSI EN 300 328 (V2.2.2) [i.8] provide a few different possible classification options which have its pros and cons. The current regulation and its interpretation as given in ETSI EN 300 328 (V2.2.2) [i.8] impose challenges for Class 1 LE devices, which are discussed below.

With the rapid evolution of the Bluetooth LE technology in response to market demand and technological developments it cannot not be excluded that further challenges will surface in addition to those identified so far.

8.2.4.1 LE Connected/Broadcast operation, in adaptive FHSS mode

ETSI EN 300 328 (V2.2.2) [i.8] provides two mechanisms for adaptive medium access: Listen Before Talk (LBT) and Detect And Avoid (DAA). Both rely on interference sensing and on the same detection threshold of -70 dBm/MHz + 10 log(100 mW/P) where P is the actual output power of the transmitter.

The Bluetooth Specification defines how channel map updates are communicated via peers in the different network topologies. This may either be after interference has been detected, or as result of preventive passive band scanning (i.e. "LBT like"), or a combination of the two methods. Additional adaptivity measures (see clause 8.2.2.1.3) are built into the technology to mitigate interference.

The current Adaptivity schemes specified in ETSI EN 300 328 (V2.2.2) [i.8] for LBT and DAA resulted from the task given by TCAM to ETSI to specify mechanisms as well as their test methods into ETSI EN 300 328 (V2.2.2) [i.8]. As the technology evolves other detection schemes such as those implemented in Bluetooth devices may better fit the intended use case and yet yield comparable or better coexistence behaviour to what LBT or DAA can provide. Alternative, technology neutral means of assessing spectrum access adaptivity are clearly required.

8.2.4.2 LE Primary Advertising operation

8.2.4.2.0 Background information

As noted in clause 8.2.3, primary vectors for growth are the Internet of Things (IoT) applications, which rely on LE as the communication link.

Primary Advertising mode is intended to facilitate rapid - and therefore efficient - establishment of a logical connection between Bluetooth devices. Consequently, it is limited to 3 of the 40 physical channels, where those are spaced in the spectrum to avoid collisions with Wi-Fi operating on the three non-overlapping 20 MHz channels (Channels 1, 6 and 11). The LE Primary Advertising mode provides support for adaptive medium access as well as passive band scanning, however that may not be implemented in all IoT devices in order to minimize battery power consumption. Product manufacturers also seek to minimize the 'air-time' for sensor nodes benefitting from the maximum available output power to achieve a long first-hop range (e.g. more than 100 m).

In some cases, manufacturers use Primary Advertising only (see clause 8.2.1.2.1) to broadcast non connectable advertising data to multiple devices at the same time as opposed to connected Bluetooth devices communicating in a peer-to-peer communication mode.

8.2.4.2.1 Primary Advertising in non-adaptive, non-FHSS mode of operation

For Class 1 LE devices, the non-adaptive, non-FHSS mode of operation is of limited use for the Primary Advertising mode of operation due to the Power Spectral Density limit set to 10 dBm/MHz.

For the Class 1 LE devices, as explained in clause 6.2.3.2.2, in the non-adaptive non-FHSS mode of operation, the maximum power output for a given duty cycle depends on the bandwidth of the device. A bandwidth of 10 MHz or more allows the use of maximum RF power output up to the 10 % duty cycle limit implied by the Medium Utilization rule.

The Primary Advertising mode operates with a bandwidth of 1,2 MHz and therefore the RF power output is limited to 10 dBm.

8.2.4.2.2 Primary Advertising in FHSS mode of operation

In assessing the non-adaptive FHSS mode for Primary Advertising, then, as explained in clause 6.2.2.2, equipment is allowed to operate on a minimum number of hop frequencies being 5 or 15 divided by the hop frequency separation whichever is greater, and where the hop frequency separation is assumed to be equal to or greater than the operating bandwidth. In the case of Primary Advertising mode, the hop frequency separation is at least 24 MHz and therefore the minimum of 5 hop frequencies applies.

For Bluetooth Class 1 devices, at 100 mW RF power output, the duty cycle is limited to 10 % over 5 hop frequencies. Because only 3 hop frequencies are actually used, the effective duty cycle is further reduced to 6 %. Clause 8.2.1.2.2 elaborates what the maximum duty cycles are for the various advertising modes; even in the worst case, advertising mostly yields a duty cycle below the 6 % (see clause 8.2.1.2.3). In future this picture may change if other applications would require a higher duty cycle.

One additional note is that the adaptivity measures defined in the Bluetooth Specification (see discussion in clause 8.4.2.1.3) also remain enabled during the Primary Advertising mode, making the LE device adaptive also in this mode, although it will not fulfil the formal adaptivity definitions of ETSI EN 300 328 (V2.2.2) [i.8] required for Class 1 LE devices, primarily because the latter stipulates a minimum of 15 hopping channels for adaptive FHSS.

8.2.4.2.3 Primary Advertising as Short Control Signalling Transmissions

Clause 8.2.1.2.3 elaborates what the maximum duty cycles are for the various advertising modes; even in the worst-case advertising yields a figure below the limits for Short Control Signalling. In more typical uses of this mode, with regular packet sizes, then the duty cycle is much lower.

ETSI EN 300 328 provides an allowance for Short Control Signalling (SCS) which allows adaptive equipment to transmit without sensing the medium for the presence of other users. Transmission is restricted to 10 % duty cycle during the dwell time or 5 ms - whichever is less.

Therefore, where Primary Advertising fits the SCS requirements, Bluetooth devices, including Class 1 LE devices, are compliant with the requirements for adaptive FHSS equipment Primary Advertising by other classes of Bluetooth devices is possible with no issues.

8.2.5 Relationship between Bluetooth technology and ETSI EN 300 328

Table 12 shows how BR/EDR and LE fits with the ETSI EN 300 328.

Table 12: Relationship between Bluetooth technology and ETSI EN 300 328

Equipment type			ETSI EN 300 328 Clause#	Technology	
				BR/EDR	LE
FHSS				☒	☒ see note 1
	Non-Adaptive Equipment:		4.3.1.6	☐	☒ see note 3
	Medium Utilization (MU) < 10 %:			☐	☒ see note 1
		P_{out} (e.i.r.p.) (dBm):			☒ see note 1
		DC (%):			☒ see note 1
	Adaptive Equipment:		4.3.1.7	☒	☒ see note 4
		Adaptive FHSS using LBT	4.3.1.7.2	☐	☐
		Adaptive FHSS using DAA	4.3.1.7.3	☒	☒ see note 1
Non-FHSS				☐	☒ see note 1
	Power Spectral Density (PSD) ≤ 10 dBm/MHz (e.i.r.p.)		4.3.2.3.1	☒	☒ see note 2 and note 3
	Non-Adaptive Equipment			☐	☒ see note 2
	Medium Utilization (MU) < 10 %:		4.3.2.5	☒ see note 1	☒ see note 1
		P_{out} (e.i.r.p.) (dBm):		☒ see note 1	☒ see note 1
		DC (%):		☒ see note 1	☒ see note 1
	Adaptive Equipment		4.3.2.6	☒ see note 1	☒ see note 1
	Adaptive non-FHSS using LBT		4.3.2.6.3	☐	☐
		Frame Based Equipment	4.3.2.6.3.2.2	☐	
		Load Based Equipment	4.3.2.6.3.2.3	☐	☐
	Adaptive non-FHSS using DAA		4.3.2.6.2	☒ see note 1	☒ see note 3
Receiver category					
	Receiver category 1		4.2.3.2.1	☒ see note 1	☒ see note 1
	Receiver category 2		4.2.3.2.2	☒ see note 1	☒ see note 1
		non-adaptive equipment with 1 % < MU ≤ 10 %		☐	☒ see note 1
		adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm		☒	☒ see note 1
	Receiver category 3		4.2.3.2.3	☒	☒
		non-adaptive equipment with MU ≤ 1 %:		☐	☒ see note 1
		adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm		☒ see note 1	☒ see note 1

NOTE 1: Depending on implementation.
NOTE 2: See clause 8.2.4.2.1.
NOTE 3: See clause 8.2.4.2.2.
NOTE 4: See clause 8.2.4.2.3.

8.3 IEEE 802.15.4-2020 technology

8.3.1 Introduction

IEEE 802.15.4-2020 [i.12] is one of the industry standards developed by the IEEE 802.15.4-2020 [i.12] working group. Its focus is on low energy consumption, low throughput short range communications typical for on-premises wireless IoT. It covers a range of frequencies, including the 2,4 GHz band. The PHY and MAC layers provided for the 2,4 GHz band are the basis for the Zigbee, Thread and other industry standards, each of which defines specific upper layers providing communications flow control, network configuration and management and other functions that are specific to certain market segments or applications.

While the IEEE 802.15.4-2020 [i.12] is also the underlying technology for the industrial automation standards WirelessHART [i.32] and ISA100.11a [i.33], these specific technologies are not covered by the present clause 8.3 but are covered by a separate clause 8.4 for WirelessHART [i.32] and clause 8.5 for ISA100.11a [i.33].

The current version of the IEEE 802.15.4-2020 [i.12] standard covers a very wide range of applications and frequency bands and provides specific profiles.

The applications of this technology include:

- Smart Utility Network (SUN).
- Rail Communications And Control (RCC).
- Radio Frequency Identification (RFID).
- Low-Energy, Critical Infrastructure Monitoring (LECIM).
- Medical Body Area Network (MBAN) services.
- Personal Area Networks (PAN).

The IEEE 802.15.4-2020 [i.12] standard defines two basic device types: the Full Function Device and the Reduced Function Device. The latter typically rely on the former for such functions as network establishment and coordination.

The bandwidth of the 2,4 GHz IEEE 802.15.4-2020 [i.12] systems is 2 MHz, the channel spacing is 5 MHz for 16 channels covering the whole 2,4 GHz band. Offset Quadrature Modulation with 32/4 direct sequence spreading is used giving a data rate of 250 kb/s. In combination with spread spectrum modulation, this provides a robust data transmission technology with a low interference profile.

IEEE 802.15.4-2020 [i.12] provides two low energy features: coordinated sampled listening (CSL) and receiver-initiated transmission (RIT). These reduce energy consumption by allowing devices to communicate while maintaining low duty cycles. CSL allows receiving devices to periodically sample the channel(s) for incoming transmissions at low duty cycles. The receiving device and the transmitting device are coordinated to reduce transmitting overhead. RIT allows receiving devices to periodically broadcast data request frames, and transmitting devices only transmit to a receiving device upon receiving a data request frame.

8.3.2 Technical description

8.3.2.1 Transmitter parameters

8.3.2.1.0 General

The following clauses reference the IEEE 802.15.4-2020 [i.12] standard, in particular the parts related to the use of the 2,4 GHz ISM band of chapter 21 which specifies the Offset QPSK -DSSS PHY.

8.3.2.1.1 Channelization

The IEEE 802.15.4-2020 [i.12] standard provides for 16 channels spaced at 5 MHz according to the formula:

$$F_c = 2\,405 + 5\,(k - 11) \text{ in MHz, for } k = 11, 12, \ldots, 26.$$

Normal operation is on one channel which may be fixed or set dynamically to operate at channels that are least interfered with.

8.3.2.1.2 RF Output Power

Transmitter output power varies with application and is restricted by country or regional specific regulatory requirements. The usual range is 1 to 100 mW e.i.r.p. which provides a range up to 100 m, although in certain regions higher power levels (e.g. up to 1 W) are allowed.

8.3.2.1.3 Modulation and Occupied Channel Bandwidth

For the 2,4 GHz band, the IEEE 802.15.4-2020 [i.12] standard specifies Direct Sequence Spread Spectrum and Offset-QPSK modulation. The chip rate is 2 000 kchips/second. Depending on the bit mapping used, the transmission data-rates vary from 62,5 kb/s to 500 kb/s.

The -20 dB bandwidth of IEEE 802.15.4-2020 [i.12] devices operating in the 2,4 GHz band is typically in the range from 2 MHz to 2,5 MHz.

8.3.2.1.4 Medium Access Methods

The IEEE 802.15.4-2020 [i.12] standard defines a number of access methods that allows the technology to adapt to a variety of requirements and environments:

- Unslotted CSMA/CA used in non-beacon-enabled PANs
- Slotted CSMA/CA used in beacon-enabled PANs
- TSCH CCA used in non-shared slots in a TSCH PAN
- TSCH CSMA/CA used for shared slots in a TSCH PAN
- CSMA/CA with priority channel access (PCA) in for critical events
- LECIM ALOHA with PCA for low energy applications

TSCH stands for adaptive time slotted channel hopping and LECIM for low energy time critical applications; PCA stands for Priority Channel Access.

Except for the non-beacon modes, communication makes use of beacons. Within the beacon periods, contention access based on CSMA/CA with a priority access feature and scheduled access are available. A beacon-based synchronization method is provided as an option. It allows PAN (sub) networks to synchronize their medium access so as to avoid unnecessary collisions.

The IEEE 802.15.4-2020 [i.12] standard provides for:

CCA Mode 1: *Energy above threshold.* Indicates a busy medium upon detecting any energy above the ED threshold.

CCA Mode 2: *Carrier sense only.* Indicates a busy medium only upon the detection of a signal compliant with this standard with the same modulation and spreading characteristics of the PHY that is currently in use by the device.

CCA Mode 3: *Carrier sense with energy above threshold.* Indicates a busy medium using a logical combination of:

- Detection of a signal with the modulation and spreading characteristics of this standard
- Energy above the ED threshold, where the logical operator may be AND or OR

CCA Mode 4: ALOHA. No channel assessment.

Which mode is used is determined by the manufacturer. The standard notes that in some regions, the use of certain CCA modes might be required to comply with the regulations applicable in that region. For operation in Europe as an Adaptive system and with a power level above 10 mW, only CCA mode 1 and CCA mode 3 (providing the logical operator is an 'OR') will result in compliant operation.

8.3.2.1.5 Transmitter unwanted emissions

The IEEE 802.15.4-2020 [i.12] standard specifies that equipment has to comply with national regulations. Therefore, equipment put on the market in Europe complies with the limits defined for transmitter unwanted emissions in the spurious and out of band domain as defined in ETSI EN 300 328 (V2.2.2) [i.8].

8.3.2.2 Receiver parameters

8.3.2.2.1 Receiver Sensitivity

The IEEE 802.15.4-2020 [i.12]standard specifies a minimum receiver sensitivity of -85 dBm at a PER of 1 %.

8.3.2.2.2 Receiver Selectivity

The IEEE 802.15.4-2020 [i.12] standard specifies interference rejection at 0 dBm C/I in the adjacent channel and at -30 dBm C/I in the second adjacent channel.

8.3.2.2.3 Receiver Blocking

The IEEE 802.15.4-2020 [i.12] standard does not specify a separate blocking requirement.

8.3.3 Networking Standards

8.3.3.0 Background information

IEEE 802.15.4-2020 [i.12] is the basic technology standard underlying industry standards for specific applications; these include the Working Group Connected Home over IP, Thread and Zigbee.

The ISA100-11a [i.33] and WirelessHART [i.32] technologies are covered in clause 8.5 and clause 8.6 respectively.

8.3.3.1 Connected Home over IP (CHIP) Project

The Project Connected Home over IP is a new Working Group that plans to develop and promote the adoption of a new, royalty-free connectivity protocol standard to increase compatibility among smart home products. The Project will define a specific set of IP-based networking technologies for device certification. It is expected that devices for compliance with this protocol standard implements at least one supported technology and not necessarily all.

The project will leverage existing PHY and MAC standards, including. The goal of the first specification release will be Wi-Fi, up to and including (draft) IEEE P802.11ax [i.11] (aka Wi-Fi 6), that is 802.11a/b/g/n/ac/ax; Thread over IEEE 802.15.4-2006 [i.15] at 2,4 GHz; and IP implementations for Bluetooth Low Energy, version 4.2 [i.29] and version 5.0 [i.28] for the network and physical wireless protocols.

8.3.3.2 Thread Networking

8.3.3.2.0 Background information

Thread is an IP-based network protocol. As such, it is suitable to carry multiple different application layers on the same network (similar to Wi-Fi). Sharing the same IP network technology between different applications (industry verticals) is desirable, because it potentially lowers the likelihood of collisions compared to the use of multiple (uncoordinated) networks in the same location and it reduces the overhead for network operation. In low power/low data-rate applications, the data throughput used for network overhead typically (by far) exceeds the actual payload throughput.

The Thread Group (www.threadgroup.org) has defined a mesh networking protocol intended as a carrier for IPv6 based application layers and product eco-systems in home and building automation, lighting, metering, smart farming, smart retail, physical security, health care and other Internet of Things (IoT) applications. Formed in 2014, the Thread Group is focused on making the Thread protocol the foundation for the IoT. Thread is a low power wireless networking protocol that enables direct, end-to-end, secure and scalable connectivity between IoT devices, mobile devices, and the Internet. The Thread Group provides a certification program to ensure device interoperability on the network layer. The Thread 1.1 [i.24] specification is publicly available and certifiable. Publication of Thread 1.2 [i.25] is expected for Q4 2020.

Thread over IEEE 802.15.4-2006 [i.15] at 2,4 GHz is one of the initial platforms that will be supported by the Connected Home over IP Project (CHIP).

8.3.3.2.1 Underlying technologies

The Thread standard is based on IEEE 802.15.4-2006 [i.15] for link type 1 and on IEEE 802.15.4-2015 [i.13] for link type 2. Its focus is on low power, low throughput short range communications typical for on-premises wireless IoT. Thread complies with the power consumption and stand-by requirements typically existing in regulations dealing with home and building automation and lighting.

The Thread protocol (Thread 1.2 [i.25]) currently allows three different link types:

1) IEEE 802.15.4-2006 [i.15] 2,4 GHz PHY and MAC with 6LoWPAN adaptation (IETF RFC 4944 [i.49] and IETF RFC 6282 [i.50])

2) IEEE 802.15.4-2015 [i.13] 2,4 GHz PHY and MAC with 6LoWPAN adaptation (IETF RFC 4944 [i.49] and IETF RFC 6282 [i.50])

3) Bluetooth Core Specification v4.2 [i.29] or higher

The technical description below focusses on link type 1 and 2. Link type 3 utilizes Bluetooth point-to-point links as a carrier technology for the Thread network layer, e.g. for direct interaction with smart devices not featuring an IEEE 802.15.4-2015 [i.13] radio. See clause 8.2 (Bluetooth) for specifics on link type 3.

Thread Interfaces may operate using a low latency, high availability of their receiver function by implementing receiver-on-when-idle (rx-on-when-idle) link modes. Alternately, Thread Interfaces may operate with a low duty cycle of their receiver capacity by implementing receiver-off-when-idle (rx-off-when-idle) link modes optimized to preserve device resources (e.g. usage of rx-off-when-idle link modes helps limiting the power consumption of battery-powered devices).

Thread 1.2 adds the use of Coordinated Sampled Listening (CSL) mode of IEEE 802.15.4-2015 [i.13]. CSL defines receiver device operation where the channel is sampled based on time coordination or synchronization to further reduce the power consumption. This allows rx-off-when-idle operation for end devices without polling.

Because of the PSD limit of 10 dBm/MHz e.i.r.p. in Europe and the relative low bandwidth of Thread devices, the maximum transmit power of Thread devices is about 13 dBm e.i.r.p.

8.3.3.2.2 Duty Cycle

The theoretical maximum duty cycle of a Thread device has been calculated to be about 66 %. Disregarding infrequently occurring peak traffic conditions - e.g. an over-the-air firmware update - the typical Thread device will have duty cycle that is an order of magnitude less.

8.3.3.2.3 Adaptivity (e.g. LBT)

Thread technology-based equipment generally uses unslotted CSMA/CA as defined in the IEEE 802.15.4-2015 [i.13] standard to avoid transmission in a channel in the presence of an interfering signal in that channel.

Thread technology-based equipment typically operates with an output power of 0 dBm. When operating at power levels above 10 dBm, European regulations require the use of a listen before talk (LBT) mechanism to avoid transmission in a channel in the presence of an interfering signal in that channel. See clause 8.3.2.1.3.

Thread technology allows the use of clear channel assessment (CCA) modes 1, 2 and 3 as per IEEE 802.15.4-2015 [i.13] specification. See clause 8.3.2.1.4.

8.3.3.3 Zigbee Networking

8.3.3.3.1 Introduction

The Zigbee PRO mesh networking protocol is maintained by the Zigbee Alliance (http://zigbee.org). Together with additional application layer specifications, it forms the basis of the Zigbee 3.0 (which is a 2015-dated unification of the Zigbee Light Link, Zigbee Home Automation and ZigBee Building Automation profiles existing before, and interoperable with the earlier products based on those) as well as Zigbee Smart Energy specifications (for the latter also refer to EN 16836-2 [i.22] and EN 16836-3) [i.23].

The Zigbee standard is based on IEEE 802.15.4-2020 [i.12], which is one of the industry standards developed by the IEEE 802.15 working group. Its focus is on low energy consumption, low throughput short range communications typical for on-premises wireless IoT. The latest release of the Zigbee PRO specification is based on IEEE 802.15.4-2015 [i.13]. Zigbee PRO originally selected a set of the optional features of the IEEE 802.15.4-2003 [i.41] standard release; it was extended with selected optional features of later IEEE 802.15.4 releases (including IEEE 802.15.4-2011 [i.14] and IEEE 802.15.4-2015 [i.13]).

The Zigbee PRO mesh network topology, allows data to be relayed by a self-organizing, self-healing mesh network of routers in order to bridge distances too large to be covered by a single point-to-point radio link. In total the Zigbee PRO standard defines the following device types:

- Router: Device which can route messages for other devices in the same Personal Area Network (PAN).
- Coordinator: Router which starts a Zigbee PAN.
- End Device: Often sleepy and battery powered device, which communicates with the PAN via a parent router.
- Green Power Device: Potentially battery less and energy harvesting device, which communicates with the PAN via one or more routers with additional Green Power proxy function.

The applications of this technology include:

- Smart Metering.
- Residential and professional lighting.
- Residential and professional HVAC.
- Residential and professional safety and security applications.
- Controls and sensors.
- Industrial Controls.

ZigBee equipment is predominantly operating in the 2,4 GHz frequency band, which is outlined in this clause, however there are also sub-GHz PHYs adopted by the ZigBee Alliance for specific use cases. These are ignored here as they are not in scope of the present document.

Because the current 2,4 GHz regulation in Europe limits the Power Spectral Density (PSD) of non-FHSS devices to 10 dBm/MHz e.i.r.p., the transmit power of Zigbee devices needs to be reduced to approximately 13 dBm e.i.r.p. for the use in the European Union.

8.3.3.3.2 Spectrum sharing

When starting a ZigBee PAN the coordinator is able to perform:

1) an active scan to search for other ZigBee Networks on any of the channels;
2) a passive scan to detect the energy level on any of the channels;

and in turn will pick the quietest channel.

Normal operation of the ZigBee network then remains on the originally chosen channel. This channel may be adjusted dynamically to adapt to local interference conditions using a feature called Frequency Agility. This Frequency Agility requires a device called the Network Manager (typically the coordinator) to identify and act upon an interference condition. This functionality is not an optional feature of the Zigbee Specification.

End devices and specifically sleepy end devices stay in contact with the network by sending a periodic data request to their parent router. The interval of this data request may vary depending on the use case and state of operation of the respective end device. Intervals can vary between once a second during a firmware update to once every number of days in case of a sensor node which rarely has data to report. In case an end device is required to receive data from the network without fail the maximum interval between data requests needs to be 7,68 s as this is the longest period a parent router will buffer data for its end device child.

8.3.3.3.3 Duty Cycle

Similar to Thread, the theoretical maximum duty cycle of a Zigbee device has been calculated to be about 66 %. With practical implementations it is difficult to reach this number, and outside of peak traffic conditions like over the air firmware upgrades, a typical Zigbee device will have a duty cycle of at least an order of magnitude below this theoretical figure.

8.3.3.3.4 Adaptivity (e.g. LBT)

Similar to Thread, ZigBee [i.21] technology-based equipment generally uses unslotted CSMA/CA as defined in the IEEE 802.15.4-2020 [i.12] standard to avoid transmission in a channel in the presence of an interfering signal in that channel.

ZigBee [i.21] technology-based equipment typically operates with an output power of below 10 dBm e.i.r.p. When operating at power levels above 10 dBm, European regulations require the use of a listen before talk (LBT) mechanism to avoid transmission in a channel in the presence of an interfering signal in that channel. See clause 8.3.2.1.3.

ZigBee [i.21] allows the use of clear channel assessment (CCA) modes 1, 2 and 3 as per IEEE 802.15.4-2015 [i.13] specification. See clause 8.3.2.1.4.

8.3.4 Market information

8.3.4.1 Thread

Despite that the market penetration of Thread-based products is still lower than other low power network technologies, it is expected that Thread as an IP based low power network technology will win significant market share in the coming years. Multiple eco-systems (KNX, BACnet, DALI …) are working on, or already offer IP based versions of their application languages running on top of Thread. Integration of sensor/actuator networks with internet services (software-based/cloud-based services) drives the need for IP based connectivity to the end-node. Data-privacy and IoT security concerns drive the need for end-to-end encryption for IoT devices exchanging data with internet-based services.

The current market penetration of Thread is estimated to be in the range of 10 million units. Industry leaders recently announced to cooperate in the development and promotion of the "Connected Home over IP" technology, where Thread is one of the targeted network protocols (www.connectedhomeip.com).

8.3.4.2 ZigBee and ZigBee PRO

Overall figures for the IEEE802.15.4-2020 [i.12] devices markets are not available but the figures for the largest commercial version - Zigbee - give an indication of current status and potential. Zigbee module market is projected to witness a compound annual growth rate of 40,38 % during the forecast period, reaching a total market size of € 38 billion in 2023 from €5 billion in 2017.

See also https://www.prnewswire.com/news-releases/global-zigbee-module-market-2018-2023-key-players-are-atmel-digi-nxp-semiconductors-renesas-electronics-silicon-laboratories-stmicroelectronics-texas-instruments-and-telink-semiconductor-300637272.html [i.46].

ZigBee [i.21] addresses a number of growing verticals ranging from Smart Energy to Home Automation, but also has some coverage in retail services, industrial automation as well as commercial buildings. Forecasts by market researchers estimate compound annual growth rates of between 8 % and 9,4 % leading to a market for Zigbee capable Systems-on-Chip of an estimated € 3,1 Billion in 2023. It is estimated that by 2024 the annual IEEE 802.15.4-2020 [i.12] chipset shipments will reach 1 Billion units per year with Zigbee being the dominating technology making use of this underlying standard.

See also https://www.marketresearchfuture.com/reports/zigbee-market-2617 [i.48] or https://onworld.com/news/1-Billion-802.15.4-Chipset-Shipments-by-2024.html [i.47].

8.3.5 Challenges

8.3.5.0 Background information

As described above, many standards for industrial and consumer networking and other data transmission applications use technology based on a subset of the IEEE 802.15.4-2020 [i.12] standard for the 2,4 GHz band, notably the DSSS PHY using Offset QPSK modulation. The dominant applications are the Internet of Things and Machine to Machine communications. Common characteristics are low data rates and low duty cycles, small form factors and battery operation. The operating range required in these applications varies from less than 10 m in-doors to approximately 100 m outdoor.

The regulations in Europe (see clause 5) for Non-Specific SRD allow for a maximum output power of 10 mW e.i.r.p. Wideband Data Transmission systems are allowed to transmit up to 100 mW e.i.r.p. providing they respect the PSD limit of 10 mW/MHz e.i.r.p. Due to the relatively narrow bandwidth of technology IEEE 802.15.4-2020 [i.12] the maximum usable output power is 13 dBm e.i.r.p. For many use cases, IEEE 802.15.4-2020 [i.12] devices will operate below this limit, however there might be use cases that would benefit from a higher output power.

NOTE: Because of the limited modulation bandwidth, frequency selective fading is an issue in many deployments and this has led to the implementation of a "slow frequency hopping" scheme that adds robustness to the overall operation. See also clause 8.4.2.1.1 .This mode of operation is not consistent with the classical notion of frequency hopping that underlies the current regulation.

8.3.5.1 Implications of the 10 mW/MHz e.i.r.p. limit

Whereas the total power limit of 100 mW e.i.r.p. is generally considered sufficient, the PSD limit of 10 mW/MHz e.i.r.p. further restricts the total e.i.r.p. of 2,4 GHz equipment based on IEEE 802.15.4-2020 [i.12] to 20 mW e.i.r.p.; this, in turn, reduces the operating range especially indoors where most of the IEEE 802.15.4-2020 [i.12] devices are deployed. There are situations and applications, e.g. for security sensors, which demand some margin in the link budget and where operation near the receiver sensitivity limit causes transmission failures and therefore a higher rate of retransmissions. These applications would benefit from a higher Power Spectral Density limit by which these unnecessary retransmissions or the use of range extenders could be avoided.

8.3.5.2 Restricted modes of adaptive medium access

ETSI EN 300 328 specifies two mechanisms for adaptive medium access: Listen Before Talk (LBT) and Detect And Avoid (DAA). Both rely on real-time interference sensing and on the same detection threshold of -70 dBm/MHz + 10 log(100 mW/P) where P is the actual output power of the transmitter.

In order to not restrict the market to two mechanisms, going forward it may be worth to investigate if other adaptivity mechanisms can be defined that will ensure other users using existing mechanisms to have equal access to the spectrum.

Ideally mechanisms for sharing spectrum should be technology independent and therefore it would be sufficient to describe the required outcome (performance), rather than describing the details of the mechanism. Concerns have been expressed that this may enable abuse resulting in unfair access to the spectrum.

8.3.6 Relationship between the IEEE 802.15.4 technology standard and ETSI EN 300 328

Table 13 shows how ZigBee [i.21] and Thread [i.25] fit with the current regulation and ETSI EN 300 328 (V2.2.2) [i.8].

Table 13: Relationship between the IEEE 802.15.4 technology standard and ETSI EN 300 328

Equipment type			ETSI EN 300 328 Clause#	Technology	
				ZigBee	**Thread**
FHSS				☐	☐
	Non-Adaptive Equipment:		4.3.1.6	☐	☐
	Medium Utilization (MU) < 10 %:			☐	☐
		P_{out} (e.i.r.p.) (dBm):			
		DC (%):			
	Adaptive Equipment:		4.3.1.7	☐	☐
		Adaptive FHSS using LBT	4.3.1.7.2	☐	☐
		Adaptive FHSS using DAA	4.3.1.7.3	☐	☐
Non-FHSS				☒	☒
	Power Spectral Density (PSD) ≤ 10 dBm/MHz (e.i.r.p.)		4.3.2.3.1	☒	☒
	Non-Adaptive Equipment			☐	☐
	Medium Utilization (MU) < 10 %:		4.3.2.5	☐	☐
		P_{out} (e.i.r.p.) (dBm):		see note	see note
		DC (%):		see note	see note
	Adaptive Equipment		4.3.2.6	☒ see note	☒ see note
	Adaptive non-FHSS using LBT		4.3.2.6.3	☒ see note	☒ see note
		Frame Based Equipment	4.3.2.6.3.2.2	☐	☐
		Load Based Equipment	4.3.2.6.3.2.3	☒	☒
	Adaptive non-FHSS using DAA		4.3.2.6.2	☐	☐
Receiver category					
	Receiver category 1		4.2.3.2.1	☒ see note	☒ see note
	Receiver category 2		4.2.3.2.2	☒ see note	☒ see note
		non-adaptive equipment with 1 % < MU ≤ 10 %		☐	☐
		adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm		☒	☒
	Receiver category 3		4.2.3.2.3	☐	☐
		non-adaptive equipment with MU ≤ 1 %:		☐	☐
		adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm		☐	☐
NOTE: Depending on implementation.					

8.4 WirelessHART technology

8.4.1 Introduction

WirelessHART [i.32] is a wireless sensor technology based on the Highway Addressable Remote Transducer Protocol. Developed as a multi-vendor wireless standard, WirelessHART [i.32] was defined for the requirements of process field device networks. These networks can have hundreds of sensors all interlinked and relaying data through a WirelessHART [i.32] Gateway device designed to interface into other wired computer and control networks. It is compliant with both the EN 62591 [i.19] and the IEEE 802.15.4-2020 [i.12] standards.

The digital architecture for field and plant networks is an open wireless solution for process automation, workforce productivity and plant management. Field networks are self-organizing mesh networks designed for measurement, sensing, process control and diagnostics in harsh industrial environments. As such the protocol has only been deployed in an industrial environment and is not available in the general consumer market.

The system components typically have an output power of less than 10 dBm e.i.r.p. and operate with duty cycles well below 20 %. The WirelessHART [i.32] Protocol utilizes both a DSSS and FHSS techniques to minimize possible interference and provide for spectrum efficiency. WirelessHART [i.32] utilizes a 2,5 MHz Occupied bandwidth per each of its 16 non-overlapping channels that are spaced 5 MHz apart, however most implementations use only 15 channels.

8.4.2 Technical description

8.4.2.1 Transmitter parameters

8.4.2.1.1 RF Output Power (e.i.r.p.)

IEEE 802.15.4-2020 [i.12] WirelessHART [i.32] industrial equipment used in different applications will have different power levels. Most devices are expected to use e.i.r.p. levels lower than the maximum limit for various reasons such as power consumption, distance between fixed devices and the density of the mesh network.

Wireless HART devices are typically fixed and located within the boundaries of an industrial site. This fact makes it very unlikely they would produce any interference beyond the industrial site.

A most unique characteristic of the WirelessHART [i.32] system is that it is effectively a hybrid device that utilizes both techniques of signal spreading simultaneously (I.e. wideband DSSS and FHSS). The WirelessHART [i.32] device typically has an occupied bandwidth of 2,5 MHz while typically utilizing 15 hopping channels.

8.4.2.1.2 Power Spectral Density

WirelessHART [i.32] equipment has a Power Spectral Density that is below the applicable limit of 10 dBm/MHz e.i.r.p. in any of its operational modes when operated as a DSSS type unit.

The Power Spectral Density requirement forces equipment to spread its energy in the frequency domain and as such reduces the potential of interference into other systems.

8.4.2.1.3 Occupied Channel Bandwidth

WirelessHART [i.32] equipment operating in the 2,4 GHz band only has one mode. This mode will have an occupied channel bandwidth of approximately 2,5 MHz per channel. This effectively utilized the entire 2,4 GHz band minimizing the potential for both TX and RX interference.

Table 14: Bandwidth distribution

Channel bandwidth	Number of Channels	Channel spacing
2,5 MHz	16	5 MHz

8.4.2.1.4 Channel Access Parameters

8.4.2.1.4.1 Duty Cycle

WirelessHART [i.32] devices maintain a DC of < 20 %. This is the maximum sustained rate. The typical WirelessHART [i.32] Mesh System will operate at < 1 %.

8.4.2.1.4.2 Medium Utilization

WirelessHART [i.32] equipment maintains an MU of 10 % or less.

8.4.2.1.4.3 Adaptivity (e.g. LBT)

WirelessHART [i.32] equipment has not employed any automatic adaptivity capabilities to date. The WirelessHART [i.32] protocol standard includes provisions for implementing LBT but the augmented power consumption due to the increased receiver activity on these battery powered devices and the need for deterministic data transport make this coexistence strategy unattractive for many industrial wireless sensing and control applications. However, the use of low TX power, hybrid DSSS and FHSS characteristics, low duty cycles, and non-mobile fixed location devices that are operated in industrial locations away from consumer settings makes this technology sufficiently polite and causes less interference into other SRDs than most other 2,4 GHz systems.

8.4.2.2 Receiver parameters

8.4.2.2.1 Receiver Spurious Emissions

WirelessHART [i.32] equipment complies with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8] which are based on ERC Recommendation 74-01 [i.18].

8.4.2.2.2 Receiver Blocking

WirelessHART [i.32] equipment complies with the Receiver Blocking requirements defined for Category 2 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.4.2.3 Antenna information

WirelessHART [i.32] devices can utilize either integral or dedicated antenna assemblies. The various combinations available are chosen based on the application needs of the system. All possible options are fully compliant with the applicable regulation.

8.4.3 Market information

WirelessHART [i.32] is a wireless sensor technology developed as an open architecture wireless standard. WirelessHART [i.32] was defined for the requirements of process field device networks. As such it is not a consumer product. Its primary purpose is to support the needs of industrial facilities to better operate, manage, maintain, and process the ever-growing data needed to manage the safe and efficient production of their products

WirelessHART is a fast-growing industrial process control protocol that has over 50 thousand systems deployed and billions of operating hours of use in over 150 countries worldwide.

8.4.4 Relationship between the WirelessHart technology and ETSI EN 300 328

8.4.4.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.4.4.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☒

Non-Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU) < 10 %: ☒

P_{out} (e.i.r.p.): 17 dBm

DC: <20 %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.4.4.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☒

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☒

Medium Utilization (MU) < 10 %: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): 13 dBm

DC: <20 %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.4.4.1.3 Receiver category

Receiver category 1: ☐

Receiver category 2: ☒

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☒

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☐

Receiver category 3: ☐

Non-adaptive equipment with MU ≤ 1 %: ☐

Adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm (e.i.r.p.): ☐

8.5 ISA100.11a technology

8.5.1 Introduction

ISA100.11a [i.33] is part of a family of standards designed to support a wide range of wireless industrial plant needs, including process automation and factory automation. The ISA100.11a [i.33] was originally an ANSI standard and later become international standard, IEC 62734 [i.33]. ISA100.11a [i.33] is an open wireless network protocol with IPv6 addressability makes ISA100.11a [i.33] compatible with the Internet of Things (IoT). The ISA100.11a [i.33] standard is designed to meet IoT market needs along with process and factory automation. The ISA100.11a [i.33] is flexible and scalable to 1 000's of sensors in a single network with sensor mesh routing over multiple hops. ISA100.11a [i.33] was developed by major automation companies, industry experts and end-user together through the International Society of Automation (ISA) a U.S.-based, non-profit organization made up of about 20 000 automation professionals. ISA standards are also widely used outside the U.S.

The radio technology uses a combination of channel-hopping and direct-sequence spread spectrum (DSSS) to achieve coexistence with other users of the same spectrum. Networks can occupy the same physical space and radio spectrum without blocking one another. ISA100.11a [i.33] uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance), LBT (listen before talk), CCA (clear channel assessment) technology to ensure co-existence with other unmanaged wireless devices using the same 2,4 GHz frequency spectrum. ISA100.11a [i.33] utilizes a 2,5 MHz Occupied bandwidth in 16 non-overlapping channels that are spaced 5 MHz apart, however most implementations use only 15 or lesser channels. The ISA100.11a [i.33] standard defines a mechanism to select frequency channels out of 15 available channels, create hybrid frequency hopping pattern and distribute the same for network devices to operate with the new hybrid frequency hopping pattern for the network operation. The ISA100.11a [i.33] network and transport layers are based on 6LoWPAN, IPv6 and UDP standards.

ISA100.11a [i.33] defines the protocol stack, system management and security functions for use over low-power, low data rate wireless networks (currently IEEE 802.15.4-2020 [i.12]). ISA100.11a [i.33] defines an object oriented application layer protocol with more than one application process with multiple transducer blocks in each application process.

The ISA100.11a [i.33] data link layer is unique to ISA100.11a and uses a non-compliant form of the IEEE 802.15.4 [i.12] MAC.

The ISA100.11a [i.33] network supports:

- mesh, star-mesh and star topologies;
- routing and non-routing sensor nodes, easy to convertor a routing sensor to a non-routing sensor and vice versa;
- connection to a plant network via a gateway;
- device interoperability;
- security - data integrity, privacy, authenticity, replay and delay protection;
- coexistence with other wireless networks;
- robustness in the presence of interference.

8.5.2 Technical description

8.5.2.1 Transmitter parameters

8.5.2.1.1 RF Output Power (e.i.r.p.)

The ISA100.11a physical layer is based on the IEEE 802.15.4-2006 [i.15] 2,4 GHz DSSS. The RF power levels provided by equipment vary between 0 dBm and 30 dBm and depend on device function and deployment requirements. The actual power levels used in a given system depend on local radio regulations.

The ISA100.11a [i.33] equipment operates in Hybrid FHSS mode, it uses DSSS modulation and does Frequency Hopping on 15 IEEE 802.15.4-2006 [i.15] frequency channels.

As a non-adaptive frequency hopping equipment with < 10 % Medium Utilization (MU), with maximum of 15 % Duty-cycle, ISA100.11a [i.33] devices limit the maximum e.i.r.p. level to 18 dBm.

8.5.2.1.2 Power Spectral Density

The ISA100.11a [i.33] has a Power Spectral Density of less than or equal to 10 dBm e.i.r.p. per MHz.

8.5.2.1.3 Occupied Channel Bandwidth

The ISA100.11a [i.33] equipment operating in the 2,4 GHz band has an occupied channel bandwidth of approximately 2,5 MHz per channel.

8.5.2.1.4 Channel Access Parameters

8.5.2.1.4.1 Duty Cycle

The duty cycle and transmission intervals of ISA100.11a [i.33] vary widely with device function and application. However, the majority of the applications are for remote sensors and/or actuators that are generally battery powered. This limits the median duty cycle to very low figures. Typical ISA100.11a [i.33] sensors in routing mode utilizes duty cycle < 15 % and sensors with non-routing mode utilizes < 5 % duty-cycle.

8.5.2.1.4.2 Medium Utilization

ISA100.11a [i.33] equipment is expected to have a maximum MU of 10 %.

8.5.2.1.4.3 Adaptivity (e.g. LBT)

The ISA100.11a [i.33] data link layer allows time synchronization of devices through accurate time stamping. Adaptive channel-hopping increases reliability by avoiding occupied channels. In addition, the time synchronized slots and channel-hopping reduce the utilization of any single channel, thereby improving the ISA100.11a [i.33] coexistence with other RF networks in the same spectrum. The channel-hopping function allows ISA100.11a [i.33] networks to optimize their use of the available spectrum by avoiding frequencies used by other spectrum users as well as avoiding frequencies subject to fading. The Listen Before Talk (LBT) capability is defined in the ISA100.11a [i.33] standard but also provides a mechanism to disable LBT mode. This makes adaptivity an optional feature in ISA100.11a [i.33], making ISA100.11a [i.33] nodes as non-adaptive nodes. For industrial process automation, the usual restricted area access provides additional mitigation to prevent possible interferences.

8.5.2.1.4.4 Tx-sequence and Tx-Gap

The ISA100.11a [i.33] utilizes a 10-ms time slots for communicating with other ISA100.11a [i.33] nodes in the network. The maximum transmission period (Tx-Sequence) is 4 ms for all ISA100.11a [i.33] nodes and the minimum Tx-gap time is 5 ms.

8.5.2.1.4.5 Accumulated Transmit Time

ISA100.11a equipment complies with the Accumulated Transmit Time as defined in ETSI EN 300 328 (V2.2.2) [i.8] for non-adaptive FHSS equipment.

8.5.2.1.4.6 Frequency Hopping/Dwell Time

The ISA100.11a [i.33] also uses frequency hopping along with DSSS Modulation to efficiently utilize the frequency spectrum and avoid collisions with other spectrum users. The dwell time is the time between frequency changes by the equipment. For ISA100.11a [i.33] equipment, the time between frequency changes is minimum 10 ms.

8.5.2.2 Receiver parameters

8.5.2.2.1 Receiver Spurious Emissions

ISA100.11a [i.33] equipment complies with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8] which are based on ERC Recommendation 74-01 [i.18].

8.5.2.2.2 Receiver Blocking

ISA100.11a [i.33]quipment complies with the Receiver Blocking requirements defined for Category 2 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.5.3 Relationship between ISA100.11a technology and ETSI EN 300 328

8.5.3.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.5.3.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☒

Non-Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU) < 10 %: ☒

P_{out} (e.i.r.p.): 18 dBm

DC: <20 %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.5.3.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☒

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☒

Medium Utilization (MU) < 10 %: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): 14 dBm

DC: < 15 %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.5.3.1.3 Receiver category

Receiver category 1: ☐

Receiver category 2: ☒

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☒

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☐

Receiver category 3: ☐

Non-adaptive equipment with MU ≤ 1 %: ☐

Adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm (e.i.r.p.): ☐

8.6 Command and Control (C2) Systems for UAS

8.6.1 Introduction

Recent years have seen massive development in Unmanned Aircraft Systems (UAS) technology, and the market for civil UAS shows exponential growth. There are multiple of challenges in fully realizing the potential for growth for UAS. One of these challenges is meeting the spectrum requirements for UAS. Frequencies are used for command and control and identification as well as payload transmissions (e.g. onboard cameras sending information to the ground).

In 2018, European Union has set out a new civil aviation legal framework through Regulation (EU) 2018/1139 [i.34] on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, where rules on UAS were included. The UAS regulatory framework has been adopted. Commission Delegated Regulation (EU) 2019/945 [i.35] deals with equipment compliance, market surveillance and placing in the market rules. In addition, Commission Implementing Regulation (EU) 219/947 [i.36] defines the UAS operation categories and scenarios. This regulation set out three UAS operation categories based on operation risk: open, specific and certified.

Currently, for most of the use cases the radio systems for these UAS operate in the 2,4 GHz band according to ETSI EN 300 328 (V2.2.2) [i.8].

The main requirements for C2 systems for the radio link are high reliability and jamming resistance, sufficient range and low latency in order to improve the safety of flight operations.

8.6.2 Technical description

8.6.2.0 Introduction

There are a lot of different implementations of C2 systems in the market but they have some technical parameters in common. All systems operate as frequency hoppers, often in combination with a channel coding or FEC. Nearly all systems operate as bidirectional equipment where the ground unit transmits the control information and the airborne units transmit back telemetry data from various onboard sensors and information about the link quality. Some airborne units contain flight stabilization systems or GPS-based flight controllers for automatic/autonomous flight operations and safety features.

Antenna diversity for the airborne equipment using multiple receivers is standard. Some systems even have a transmitter diversity for the ground unit.

8.6.2.1 Transmitter parameters

8.6.2.1.1 RF Output Power (e.i.r.p.)

The ground units use an e.i.r.p. of 17 dBm to 20 dBm while the airborne devices often operate with a reduced power of 10 dBm to 13 dBm e.i.r.p.

8.6.2.1.2 Power Spectral Density

There is no PSD-limit for frequency hoppers. The PSD of C2 systems are in the range of the e.i.r.p. or slightly lower.

8.6.2.1.3 Occupied Channel Bandwidth

The occupied channel bandwidth ranges from 300 kHz up to 3 MHz.

8.6.2.1.4 Channel Access Parameters

8.6.2.1.4.1 Duty Cycle

There are adaptive and non-adaptive implementations of C2 equipment.

Due to the fact that C2 systems make use of the maximum possible e.i.r.p. (20 dBm) the duty cycle for non-adaptive devices is limited by the maximum MU of 10 % and therefore the duty cycle stays below 10 %.

For adaptive C2 systems there is no restriction on duty cycle but its value is typically below 40 % (depending on the implementation).

8.6.2.1.4.2 Medium Utilization

For non-adaptive C2 systems the MU stays below 10 %. For adaptive systems the MU does not apply.

8.6.2.1.4.3 Adaptivity

Adaptive C2 systems have implemented an LBT based spectrum sharing mechanism using energy detect as described in ETSI EN 300 328 (V2.2.2) [i.8].

8.6.2.1.4.4 Transmission Timing

Adaptive and non-adaptive C2 systems use frame based technology. The maximum transmission time (Channel Occupancy Time) is typically in the order of 800 µs up to 3 ms and the dwell time per hopping frequency is in the range of 8 ms up to 20 ms. For airborne devices the transmit activity is linked to the reception of a valid transmission from the ground system, it only transmits in response to a correct reception. The systems do not use retries.

8.6.2.1.5 Transmitter unwanted emissions

C2 systems are compliant with the limits defined for transmitter unwanted emissions in the spurious and out of band domain as defined in ETSI EN 300 328 (V2.2.2) [i.8].

8.6.2.2 Receiver parameters

8.6.2.2.1 Receiver Spurious Emissions

C2 systems are compliant with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8].

8.6.2.2.2 Receiver Blocking

Adaptive C2 systems are compliant with the Receiver Blocking requirements defined for Category 1 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

Non-adaptive C2 systems are compliant with the Receiver Blocking requirements defined for Category 2 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.6.2.3 Antenna information

The antenna types used by C2 systems range from simple wire antennas to circular polarized chip antennas. Besides very small micro receivers an antenna diversity with up to 4 receivers on the airborne side is standard. Some systems even have a diversity for the ground station transmitter using 2 independent transmit chains and antennas but beamforming is currently not used.

8.6.3 Market information

According to a report by the European Parliament's Committee on Transport and Tourism, the EU holds a leading edge in the civilian sector, with 2 500 operators (400 in the UK, 300 in Germany, 1 500 in France, 250 in Sweden, etc.) compared to 2 342 operators in the rest of the world. It is estimated that within the next ten years the UAS industry could be worth 10 % of the aviation market, or €15 billion per year. The Aerospace and Defence Industries Association of Europe forecast that about 150 000 UAS-related jobs will be created in Europe by 2050, excluding employment generated through operator services (source ECC Report 268 [i.20]).

The numbers above do not include the operators in the area of aeromodelling which are about 500 000 pilots and about 2 000 000 systems in Europe. There is no reliable estimation of the financial market volume but it can be assumed that this will be at least an additional amount of 50 - 100 million € per year. The complete toy mass-market is not included in these numbers.

8.6.4 Relationship between Command and Control system properties and EN300 328

8.6.4.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.6.4.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☒

For the non-Adaptive C2 systems:

Non-Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU) < 10 %: ☒

P_{out} (e.i.r.p.): 20 dBm

DC: <10 %

For the Adaptive C2 systems:

Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.6.4.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☐

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☐

Medium Utilization (MU) < 10 %: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): …… dBm

DC: ……. %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.6.4.1.3 Receiver category

For the Adaptive C2 systems:

Receiver category 1: ☒

For the non-Adaptive C2 systems:

Receiver category 2: ☒

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☒

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☐

Receiver category 3: ☐

Non-adaptive equipment with MU ≤ 1 %: ☐

Adaptive/non-adaptive equipment with P_{out} ≤ 0 dBm (e.i.r.p.): ☐

8.7 Wireless audio link for hearing impaired

8.7.1 Introduction

Wireless microphone systems have been developed for use by hearing impaired students in classrooms. They consist of two types of devices, a wireless microphone worn by the teacher and hearing aids worn by the students. These systems allow a much better understanding of the teacher's voice in classrooms by hearing impaired students, eliminating the detrimental effects of ambient noise and echoes.

In the past, such systems were operating at lower frequencies (169 MHz to 220 MHz) using analogue FM modulation.

The current systems operate in the 2,4 GHz band and uses digital modulation with FHSS. It complies with ETSI EN 300 328 [i.8] (V2.2.2). The transmitter of the wireless microphone use DAA (Detect and Avoid) as interference mitigation technique. First devices appeared on the market in 2013. The silicon technology at that time was CMOS 180 nm.

The link is asymmetrical in power. The wireless microphone has higher power (50 mW to 100 mW e.i.r.p.). It broadcasts the teacher's voice to a number of hearing aids worn by students in the classroom.

The receivers are either clipped on to or are an integral part of the hearing aids. They are miniaturized battery powered devices. They have a low power (1mW) transmitter, which serves for pairing the hearing aid with the wireless microphone, or for providing information (e.g. hearing aid battery status) on request from the wireless microphone.

Due to the difference in transmitted power, the range from the teacher's wireless microphone transmitter to the hearing aid receivers is much higher than in the opposite direction. For this reason, a specific broadcast protocol is used which does not include receiver acknowledgements. In classrooms, the range is typically 20 m.

A variant of the teacher's wireless microphone is used by hearing impaired users for e.g. improved listening to television at home, better understanding in restaurants and during meetings at work.

Another use case is the multi-talker network whereby multiple wireless microphones are possible, one being the primary microphone and the others being secondary microphones. Automatic switching takes place between the devices based on voice activity detection, with a priority set on the primary device. This allows for two or more teachers using wireless microphones in the same classroom and having distributed wireless microphones in the classroom for transmitting responses from the students.

8.7.2 Technical description

8.7.2.1 Transmitter parameters

8.7.2.1.1 RF Output Power (e.i.r.p.)

The transmitter of the teacher's wireless microphone typically has a maximum output power of 17 dBm to 20 dBm e.i.r.p.

The transmitter of the hearing aid has an output power of < 0 dBm (often ~ -10 dBm e.i.r.p. due to antenna size and body loss).

8.7.2.1.2 Power Spectral Density

Not applicable as the technology uses FHSS.

8.7.2.1.3 Occupied Channel Bandwidth

The system has an Occupied Channel Bandwidth of 1 MHz.

8.7.2.1.4 Channel Access Parameters

8.7.2.1.4.1 Duty Cycle

The transmitter of the hearing aid is a non-adaptive equipment with a DC of < 10 %.

8.7.2.1.4.2 Medium Utilization

The hearing aid devices are non-adaptive equipment with an MU < 1 %.

8.7.2.1.4.3 Adaptivity (e.g. LBT)

The teacher's wireless microphone is adaptive equipment using FHSS with DAA.

8.7.2.1.5 Transmitter unwanted emissions

The transmitters of the wireless microphone and the hearing aid comply with the limits for transmitter unwanted emissions in ETSI EN 300 328 (V2.2.2) [i.8] and which are based on ERC Recommendation 74-01 [i.18].

8.7.2.2 Receiver parameters

8.7.2.2.1 Receiver Spurious Emissions

Both the wireless microphone and the hearing aid comply with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8] and which are based on ERC Recommendation 74-01 [i.18].

8.7.2.2.2 Receiver Blocking

The wireless microphone is Adaptive equipment that complies with the Receiver Blocking requirements defined for Category 1 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

Hearing aid receivers are non-adaptive equipment with a MU < 1 % and a total power of maximum 0 dBm and therefore they comply with the Receiver Blocking requirements defined for Category 3 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.7.2.3 Antenna information

The wireless microphone uses an integral antenna. In most cases, this is a Planar Inverted-F Antenna (PIFA) which is integrated on the main PCB of device. The maximum antenna gain is between -3 dBi and +1 dBi.

For the hearing aids, depending on device type and size, either a magnetic loop antenna or a folded resonant loop antenna is used. The maximum antenna gain is -10 dBi.

8.7.2.4 New Systems

The evolution of silicon technology allows the integration of more complex radio systems in hearing aids. These systems have lower power consumption and are capable to use different transmission protocols:

- A proprietary broadcasting protocol for use in classrooms.
- Bluetooth (BR/EDR or LE) for audio links between the hearing aid and various personal devices (PC, smart phones). In the case of smart phones, the user's voice picked-up by the microphone of hearing aid can be transmitted to the cellular phone to operate hands-free.
- Another proprietary hearing aid protocol for transmitting audio from between the left and the right hearing aids. This allows a combination of left and right sound channels to further improve the hearing performance on each ear. The audio settings for both sides are synchronized through the same "binaural" wireless link.

8.7.3 Market information

Currently, worldwide hearing aid sales amount to a volume of 15 M pieces per year, with 5 % annual growth.

About 50 % of the new systems now operate in the 2,4 GHz band. It is expected that in a few years all systems will use Bluetooth and/or proprietary protocols for communication with broadcasting sound systems and for the transmission of audio between both hearing aids.

10 % of hearing impaired are currently using wireless accessories like relay-transmitters for listening to TV, microphone systems for schools, personal hand microphones for improved listening in restaurants or at work. The sale of these accessories is growing strongly.

8.7.4 Relationship between wireless audio system properties and ETSI EN 300 328

8.7.4.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.7.4.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☒

Hearing aids:

Non-Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU) < 10 %: ☒

P_{out} (e.i.r.p.): < 0 dBm

DC: < 10 %

Wireless microphone:

Adaptive Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.7.4.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☐

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☐

Medium Utilization (MU) < 10 %: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): ….. dBm

DC: ….. %

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.7.4.1.3 Receiver category

Wireless microphone:

Receiver category 1: ☒

Receiver category 2: ☐

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☐

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☐

Hearing aids:

Receiver category 3: ☒

Non-adaptive equipment with MU ≤ 1 %: ☒

Adaptive/non-adaptive equipment with $P_{out} \leq 0$ dBm (e.i.r.p.): ☒

8.8 Large scale wireless IoT mesh network connectivity equipment

8.8.1 Introduction

Large scale wireless IoT mesh network connectivity is required in many industrial and commercial settings. This equipment enables easy deployment of IoT mesh networks with extensive scalability but with minimal connectivity management and configuration needs. The Wirepas equipment can support different applications with two optimized access modes namely low latency and low energy.

The low energy and low latency profiles utilizes both frequency and time division access. The 2,4 GHz band is divided into a number of non-overlapping frequency channels. Transmissions of each individual node taking place on a single frequency channel are scheduled in time to avoid collisions with other nodes in the network. In Low Energy mode, the system applies also Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to avoid transmitting (and limit the unnecessary battery consumption) when the medium is busy.

The equipment makes the communication and routing decisions locally. These includes autonomous selection of neighbouring nodes to communicate with, the TX power levels and the frequency channels to be used for the communication. The routing supports multi-gateway operation to scale coverage and capacity within the network.

8.8.2 Technical Description

8.8.2.1 Transmitter parameters

8.8.2.1.1 RF Output Power (e.i.r.p.)

The maximum power level is 10 dBm e.i.r.p. and is dependent on equipment HW capabilities and battery capacity. The maximum TX power is used for beacon frames which are broadcasting essential control information of the network. In dense deployments, the applied power levels are much below the maximum allowed power levels, due to short link distances. The equipment implements Adaptive transmit Power Control (APC) for unicast frames, where the transmitter adjusts the TX power to be sufficient to enable reception at the intended receiver. This is done to minimize power consumption and interference to achieve maximum system capacity.

8.8.2.1.2 Power Spectral Density

The maximum Power Spectral Density is 10 dBm/MHz e.i.r.p.

8.8.2.1.3 Modulation

The modulation scheme is GFSK with 1 Ms/s physical channel symbol rate.

8.8.2.1.4 Occupied Channel Bandwidth

The Occupied Channel Bandwidth as defined in ETSI EN 300 328 (V2.2.2) [i.8] is 1,05 MHz.

8.8.2.1.5 Channelization scheme

Equipment can support 40 channels. The channel frequency separation is 2 MHz. The lowest channel centre frequency is 2 402 MHz and the highest channel centre frequency is 2 480 MHz.

8.8.2.1.6 Channel Access Parameters

8.8.2.1.6.1 Background information

The device performs channel sensing to avoid channels being used by other systems and for selecting the most suitable frequency(ies) for its operation.

The device detects transmissions from other nodes within the same network and will coordinate locally within a cluster the receive and transmit time slots for each device within a network to avoid collisions when operating on the same channel. Devices can belong to different clusters and therefore can operate on multiple channel frequencies (different per cluster) in a time slotted manner. Within a given cluster, the receiver and transmitter synchronization for each device is managed by its cluster head. Each cluster head may belong as a member to another cluster.

Each device is monitoring the link quality, and in case of poor performance (lost packages, high interference levels), they are able autonomously change the operating channel. This capability improves the communication reliability, reduces the battery power consumption and reduces the interference it may generate to the adjacent systems as it can avoid local interference sources.

The maximum duration of a single transmission of an application layer data packet is less than 1,6 ms.

8.8.2.1.6.1 Duty Cycle

The Equipment may support two operational modes:

- Low Latency/High Throughput mode for real-time control and load intensive applications
- Low Energy mode for lower throughput battery-powered applications.

Both modes can co-exist in the same network.

In the Low Latency mode, the absolute maximum transmitter duty cycle can be up to 45 %. The actual duty cycle is much lower and depends on the applied traffic load and environment.

In the Low Energy mode, the maximum duty cycle is up to 2,8 %, whereas the typical duty cycle is less than 1 %. The actual values are merely due to application data load.

The equipment supports a re-transmission scheme, which ensures a very reliable packet delivery performance.

8.8.2.1.6.2 Medium Utilization

Not applicable as the equipment operates below 10 dBm e.i.r.p. output power.

8.8.2.1.6.3 Adaptivity

Not applicable as the equipment operates below 10 dBm e.i.r.p. output power.

8.8.2.2 Receiver parameters

8.8.2.2.1 Receiver Spurious Emissions

Equipment complies with the limits defined for Receiver Spurious Emissions in ETSI EN 300 328 (V2.2.2) [i.8].

8.8.2.2.2 Receiver Blocking

Equipment complies with the Receiver Blocking requirements defined for Category 2 receivers in ETSI EN 300 328 (V2.2.2) [i.8].

8.8.2.3 Antenna information

Equipment can utilize either integral or dedicated antennas, depending on use cases and mechanical requirements.

8.8.3 Market information

Wirepas mesh equipment is designed for operating in large scale dense IoT mesh networks which can contain up to millions of devices. The equipment density (several hundred in a cubic meter) and the communication range may vary from application to application. The equipment supports real-time control, data load intensive, and low rate battery-operated applications. The main application areas are in logistics, metering, large scale indoor and outdoor lighting systems and sensor applications. The service and product introduction are ongoing with large scale deployments.

8.8.4 Relationship between the Wirepas system and ETSI EN 300 328

8.8.4.1 Equipment type *(see ETSI EN 300 328 (V2.2.2) clause 4.2)*

8.8.4.1.1 Frequency Hopping Spread Spectrum (FHSS) equipment: ☐

Non-Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.6)*

Medium Utilization (MU): ☐

P_{out} (e.i.r.p.):

DC:

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7)*

Adaptive FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.2)*

Adaptive FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.1.7.3)*

8.8.4.1.2 Other types of Wideband Data Transmission equipment (non-FHSS): ☒

Power Spectral Density (PSD) ≤ 10 dBm/MHz: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.3.1)*

Non-Adaptive Equipment: ☐

Medium Utilization (MU) < 10 %: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.5)*

P_{out} (e.i.r.p.): < 10 dBm

DC: < N/A

Adaptive Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6)*

Adaptive non-FHSS using LBT: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3)*

Frame Based Equipment: ☒ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.2)*

Load Based Equipment: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.3.2.3)*

Adaptive non-FHSS using DAA: ☐ *(see ETSI EN 300 328 (V2.2.2) clause 4.3.2.6.2)*

8.8.4.1.3 Receiver category

Receiver category 1: ☐

Receiver category 2: ☒

Non-adaptive equipment with 1 % < MU ≤ 10 %: ☐

Adaptive/non-adaptive equipment with 0 dBm < P_{out} ≤ 10 dBm (e.i.r.p.): ☒

Receiver category 3: ☐

Non-adaptive equipment with MU ≤ 1 %: ☐

Adaptive/non-adaptive equipment with $P_{out} \leq 0$ dBm (e.i.r.p.): ☐

9 Radio spectrum request and justification

The present document does not contain a new spectrum request.

History

Document history		
V1.1.1	May 2021	Publication