IEEE P802.15
Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	TG6ma Coexistence Assurance Document
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Source	Ryuji Kohno (YNU/YRP-IAI), Marco Hernandez（YRP-IAI/CWC-UoO), Daisuke Anzai (NiTech), Minsoo Kim (YRP-IAI), Seong-Soon Joo (KPST), Takumi Kobayashi (NiTech/YRP-IAI) Kento Takabayashi (ToyoU)
Re:	802.15.6ma draft2.5.2
Abstract	Analysis on coexistence of 802.15.6 with other 802 systems within the same frequency bands
Purpose	To address the coexistence capability of 802.15.6ma UWB PHY & 802.15.6-2012 UWB PHY to satisfy requirements of the IEEE 802.19 Task Group and IEEE 802 Executive Committee to determine if a proposed IEEE 802 standard has made a reasonable effort to be able to coexist with devices compliant to other IEEE 802 standards in their operating band.
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Release	The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

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1 Introduction

This document provides a summary of coexistence analysis assessment which has been performed to evaluate the performance of systems using the 802.15.6-2012 UWB PHY and MAC as revised by P802.15.6ma with respect to other 802 wireless standards which may operate in the same band.

The PAR for P802.15.6ma may be found in [1]

802 standards to consider:

- 802.11-2020 and 802.11ax-2021[2][3][4]
- Draft 802.11be (ax, be) [5]
- Legacy 802.15.6-2012[6][7]
- Legacy 802.15.4 UWB (HRP, LRP) [8]-[12]
- Draft 802.15.4ab NB and UWB [13]
- Draft 802.15.6ma UWB [14]

Addressing interference caused by IEEE 802.15.6ma to these existing systems, and interference from these existing standards with IEEE 802.15.6-2012[9].

The IEEE 802.19 TAG has mandated that new wireless standards developed under IEEE 802 be accompanied by a *Coexistence Assurance* document. In エラー! 参照元が見つかりません。, guidelines are provided for how coexistence can be quantified based on predicted packet error rates among IEEE 802 wireless devices. A detailed discussion of coexistence and coexistence methods can be found in IEEE Std 802.15.2-2003[17].

Project P802.15.6ma is the latest revision of PHY and MAC of IEEE Std 802.15.6-2012[6].

Hence, this coexistence assurance document is provided by the IEEE 802.15.6ma Task Group to satisfy the requirements of the IEEE 802.19 Task Group and IEEE 802 Executive Committee.

The IEEE 802.15 Task Group 6ma defines a Medium Access Control (MAC) layer and a PHY layer to enable Body Area Networks (BAN) used in, on, or around human and vehicle bodies.

IEEE 802.15.6ma specifies a single PHY, Ultra Wide Band (UWB) while IEEE802.15.6-2012 specified three PHYs, namely Narrow Band (NB), Ultra-Wide Band (UWB) and Human Body Communication (HBC) [4].

IEEE802.15.6ma defines MAC and PHY layers to ensure coexistence of multiple BANs for enhanced dependability.

This document addresses the coexistence of IEEE 802.15.6ma PHY system with other IEEE 802 standards operating in the same frequency bands.

The first UWB PHY was introduced in amendment IEEE Std 802.15.4a-2007, which defined an impulse radio (IR) UWB PHY with low data rates [9]. With the addition of a second UWB PHY optimized for low complexity RFID with amendment IEEE-Std 802.15.4f-2012, named Low-Rate Pulse repetition frequency (LRP) PHY. In the subsequent revision, IEEE Std 802.15.4-2015, the original UWB PHY was renamed the original UWB PHY was renamed High-Rate Pulse repetition frequency (HRP) PHY to differentiate [9][10][11]. Subsequently, amendment 802.15.4z-2020 was completed, which enhanced both LRP and HRP PHYs.

The HRP channel plan comprises three sub-band: a sub-1GHz channel plan, a low band from 3.1 GHz to 4.8 GHz, and the high band from 6.0 to 10.6 GHz. The channel plan included nominally 500 MHz channelization and optional wider channels (from 1.2 to 1.5 GHz). The 500 MHz channels have proven most popular in implementations. The LRP PHY introduced three channels from 6 GHz to 8.5 GHz, IEEE Std 802.15.4z added additional LRP channels from 8.5 to 10.6 GHz [12].

Project P802.15.6ma is enhancing dependability of the HRP and LRP PHYs under channel propagation and environment models of in and on a human and a vehicle body in growing use of UWB for medical healthcare and automotive market needs [14].

Subsequent to the completion of IEEE Std 802.15.4z-2020, IEEE Std 802.11ax-2021 was completed that included channelization in the 6 GHz to 7 GHz range, overlapping with both HRP and LRP UWB PHYs. This was considered in the coexistence assessment for project 802.15.4z in [12].

This coexistence assessment examines coexistence studies that are available, and evaluates the changes included in the P80215.6ma draft as they may potentially affect coexistence [18] according to the PAR, CSD, TRD (Technical Requirement Document), and CMD(Channel Model Document) [19][20].

The relevant 802 standards that use bands overlapping those used by the current project are identified in 4.1 and 4.2.

In addition, this project P802.15.6ma is collaborating with IEEE802,1 Amendment: Support for IEEE Std 802.15.6 to IEEE Standard 802.1AC-2016[21]

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3 Acronyms and abbreviations

ARQ	Automatic Repeat Request
AWN	Affected Wireless Network
BAN	Body Area Network
BCC	Binary Convolutional Code
BCH	Bose, Ray-Chaudhuri, Hocquenghem Code
BER	Bit Error Rate
BCI	Brain-Computer-Interface
BMI	Brain-Machine-Interface
BPSK	Binary Phase Shift Keying
CAP	Contention Access periodC
CCA	Clear Channel Assessment
CDC	Control and Data Channel
CFP	Contention Free Period
C2C	Coordinator-to-Coordginator
D-MPSK	Differential M-ary Phase Shift Keying
DAA	Detect and Avoid.
DSSS-CCK	Direct Sequence Spread Spectrum – Complimentary Code Keying
EIRP	Equivalent Isotropically Radiated Power
FEC	Forward Error Correction
FHSS	Frequency Hopping Spread Spectrum
FM-UWB	Frequency Modulation Ultra-Wide Band.
FSDT	Frequency Selective Digital Transmission
GMSK	Gaussian Minimum Shift Keying
GTS	Guaranteed Time SlotHARQ Hybrid Automatic Repeat Request (ARQ)
HBAN	Human Body Area Network
IR-UWB	Impulse Radio Ultra-Wide Band
IWN	Interfering Wireless Network
LBT	Listen Before Talk
LDPC	Low Density Parity Check
LSB	Least Significant Bit
LFSR	Linear Feedback Shift Register
MBANS	Medical Body Area Network Service
MICS	Medical Implant Communication Service
MIMO	Multiple Input, Multiple Output
MPDU	MAC Protocol Data Unit

MSB	Most Significant Bit
OFDM	Orthogonal Frequency Division Multiplexing
O-QPSK	Offset Quadrature Phase Shift Keying
PER	Packet Error Rate
PHR	PHY Header
PLCP	Physical Layer Convergence Procedure
PPDU	PHY Protocol Data Unit
PSDU	PHY Service Data Unit
PSSS-ASK	Parallel Sequence Spread Spectrum – Amplitude Shift Keying
QAM	Quadrature Amplitude Modulation
SHR	Synchronization Header
SIR	Signal to Interference Ratio
SRRC	Square Root Raised Cosine
SOCC	Super Orthogonal Convolutional Code
RS	Reed-Solomon
VBAN	Vehicle Body Area Network
WMTS	Wireless Medical Telemetry Service

4 Overview of 802.15.6ma PHY and MAC

4.1 Operating Frequency Bands

IEEE802.15.6-2012 specified three PHYs, namely Narrow Band (NB), Ultra-Wide Band (UWB) and Human Body Communication (HBC) [4]. Each PHY is specified to operate in one of a unique set of frequency bands. Thus, mutual interference between BAN PHYs is avoided.

Project P802.15.6ma is the latest revision of PHY and MAC of IEEE Std 802.15.6-2012. IEEE 802.15.6ma specifies only UWB PHY for the sake of enhanced dependability for use cases specified in human and vehicle body areas.

The defined channel plans of interest for UWB cover the frequency range from 3.1 GHz to 10.6 GHz. The actual spectrum used varies by region. The allocated frequency bands for the 802.15.6ma UWB PHY are:

Table 1—UWB operating frequency bands

Band Group	Channel Number	Central frequency (MHz)	Bandwidth (MHz)	Channel attribute
Low band	0	3494.4	499.2	Optional
	1	3993.6	499.2	Mandatory
	2	4492.8	499.2	Optional
High band	3	6489.6	499.2	Optional
	4	6988.8	499.2	Optional
	5	7488.0	499.2	Optional
	6	7987.2	499.2	Mandatory
	7	8486.4	499.2	Optional
	8	8985.6	499.2	Optional
	9	9484.8	499.2	Optional
	10	9984.0	499.2	Optional

4.2 Relevant 802 Standards

Table 2 lists the other 802 standard that may operate in overlapping bands. This information was derived from [14] and [22].

The 802.11 OFDM channel plan overlaps the UWB channel plan in the frequency range 5.925 GHz to 7.125 GHz (802.11ax) or 7.250 GHz (P802.11be).

Table 2: Other 802 Wireless Standards in the Subject Bands

Standard	Frequency Band (MHz)	PHY description	Notes
802.15.6-2012	3244–4743	HRP UWB low band	subclause 5.3
802.15.6-2012	5944–10 234	HRP UWB high band	subclause 5.3
802.15.6-2012	6289.6–9185.6	LRP UWB	subclause 5.3
802.15.4	3244–4743	HRP UWB low band	subclause 5.3
802.15.4	5944–10 234	HRP UWB high band	subclause 5.3
802.15.4	6289.6–9185.6	LRP UWB	subclause 5.3
802.11-2020	3650–3700	10, 20, 40 MHz channel spacing	clause 6
802.11-2020	4002.5	5 MHz channel spacing	
802.11-2020	4940–4990	20 MHz channel spacing	
802.11-2020 802.11ax-2021	5150–5895	10,20, 40, 80, 160 MHz channel spacing	
802.11ax-2021	5935 – 7125	10,20, 40, 80, 160 MHz channel spacing	
P802.11be (Draft)	5935-7250	10, 20, 40, 80, 160, 320 MHz channel spacing	
P802.15.4ab (Draft)	3244–4743	HRP UWB low band	subclause 5.3
P802.15.4ab (Draft)	5944–10 234	HRP UWB high band	subclause 5.3
P802.15.4ab (Draft)	6289.6–9185.6	LRP UWB	subclause 5.3

4.3 Summary of Revision

This revision enhances dependability in physical layer (PHY) and medium access control (MAC) of wireless Body Area Network (BAN) under specified channel models [20] and coexistence classes in human and vehicle body areas [14].

This project IEEE802.15.6ma started for amendment 802.15.6a of the Std. IEEE802.15.6-2012 to enhance dependability in practical channel environment with reasonable feasibility of implementation, and then changed into revision 802.15.6ma due to 10 years lifetime of the standard.

In fact, the more BANs use in dense area, the more contention and inference cause performance degradation. The IEEE802.15.6ma focuses primarily on enhanced dependability in coexistence environment of multiple same standard BANs and then assets coexistence with other IEEE802 standard networks. Although the Std. IEEE802.15.6-2012 has three PHYs; NB, UWB, and HBC and many access modes in MAC; beacon mode with beacon periods (superframes), non-beacon mode with superframes, and non-beacon mode without superframe.

IEEE802.15.6ma specifies UWB only in PHY and beacon mode only in MAC for the sake of implementation feasibility as well as enhanced dependability in coexistence environment.

The Std. IEEE802.15.6-2012 specifies short-range, wireless communications in the vicinity of, or inside, a human body but not limited to humans. For the sake of more market, the revision IEEE802.15.6ma covers on, around, and implant human BANs (HBANs) for instant brain-machine-interface (BMI), brain-computer-interface (BCI), capsule endoscope etc. for medical healthcare and vehicle BANs (VBANs) for vehicle bodies such as cars, buses, trains etc. for automotive and transportation uses, and interaction between HBANs and VBANs,

Areas of enhancement include:

- Additional channel models for HBAN and VBAN; reference Channel Model Document (CMD) [20].
- Channel coding, i.e., forward error correction (FEC) and hybrid ARQ (Automatic Repeat Request) of FEC and ARQ, i.e., HARQ for error controlling schemes to support required performance corresponding to 8 levels of QoS requirement of transmitting packets in table 3 and 8 classes of coexistence in table 4.
- Control and data channels definition and function to access control of packet contention in multiple BANs coexistence.
- Interference mitigation techniques to support greater device density and higher traffic use in coexistence classes of multiple BANs and other frequency shared networks relative to the IEEE Std 802.15.6-2012.
- Ranging between coordinators or hubs of coexisting BANs to monitor geographic and dynamic status for detection and mapping of surrounding BANs in option.
- Network topologies are extended from star and one-hop star in IEEE802.15.6-2012 to star, one-hop and two hop stars for more practical use case requirement.
- Enhanced native discovery and connection setup mechanisms.
- Mechanisms supporting enhanced dependability of HBAN, VBAN, and their mixed use cases.
- New data rates to support at least 50 Mb/s of throughput.

4.3.1 Levels of User Priority for Required Packet QoS

The std IEEE802.15.6-2012 has been referenced in prioritizing medium access of data and management type frames, based on the designation of frame payloads (traffic) contained in the frames according to 0. The traffic designation for background (BK), best effort (BE), excellent effort (EE), video (VI), voice (VO), and network control is based on some traffic types defined in Annex G.1 of IEEE Std 802.1D™-2004 エラー! 参照元が見つかりません。.

The revision 802.15.6ma also keeps the user priority for required packet QoS but priority order is determined for human and vehicle bodies use cases individually and jointly in medical healthcare and automotive applications. For instant, electrocorticogram (ECoG) of BMI is the highest priority level while human surface temperature is lower priority in HBAN. Controlling command of autonomous car driving is the highest priority level while car driving room temperature of air conditioner is lower in VBAN.

Table 3: User priority mapping

Priority	User priority	Traffic designation	Frame type
Lowest	0	Background (BK)	Data
	1	Best effort (BE)	Data
	2	Excellent effort (EE)	Data
	3	Video (VI)	Data
	4	Voice (VO)	Data
	5	Medical data or network control	Data or management
	6	High-priority medical data or network control	Data or management
Highest	7	Emergency or medical implant event report	Data

4.3.2 Classes of Coexistence Environment

The coexistence methodology uses a variant.

The draft revision supports BANs operating with high reliability in dense environments coexisting with intra-interference and inter-interference due to other wireless systems in the same frequency band. 0 shows the different coexistence environment classes considered in the standard.

Table 4; Coexistence environments

Coexistence environment class	15.6ma	15.6-2012	Non-UWB (Wi-Fi, unlicensed 5G)	802.15 UWB (15.4, 15.8)	Non-802.15 UWB (ETSI, SmartBAN)	Note
0	—	—	—	—	—	A single BAN
1	✓	—	—	—	—	Multiple BANs
2	✓	✓	—	—	—	
3	✓	—	✓	—	—	Non-UWB systems
4	✓	—	—	✓	—	Multiple UWB systems
5	✓	—	—	—	✓	
6	✓	—	—	✓	✓	
7	✓	✓	✓	✓	✓	Multiple: BANs, non-UWB and UWB systems

The configuration of the revised UWB PHY and MAC depends on the coexistence environment classes and the QoS priority levels in tables 3 and 4.

The coexistence environment classes in Table 4 are summarized as follows:

- Class 0 defines the operation of a single BAN, either HBAN or VBAN. This type of configuration enables the radio interface to be the same as 802.15.4ab harmonizing implementations.
- Class 1 defines the operation of multiple 15.6ma BANs. This environment triggers the coordinator-to-coordinator protocol for the formation of a group superframe for coexistence and enhanced dependability.
- Class 2 defines the operation of multiple 15.6ma BANs and 15.6 BANs. As in class 1, this environment triggers the coordinator-to-coordinator protocol for the formation of a group superframe and interference mitigation of legacy 15.6 BANs.
- Class 3 defines the operation of 15.6ma BANs with non-UWB systems operating in the same frequency band such as 802.11, unlicensed 5G, etc. 15.6ma BANs support interference mitigation and higher reliability via FEC mechanisms.
- Class 4 defines the operation of 15.6ma BANs with other IEEE 802.15 standards with a UWB PHY. 15.6ma BANs support interference mitigation and higher reliability via FEC mechanisms.

- Class 5 defines the operation of 15.6ma BANs with non-IEEE standards with a UWB PHY. 15.6ma BANs support interference mitigation and higher reliability via FEC mechanisms.

- Class 6 defines the operation of 15.6ma BANs with other IEEE 802.15 standards with a UWB PHY and other non-IEEE standards with a UWB PHY. 15.6ma BANs support interference mitigation and higher reliability via FEC mechanisms.

- Class 7 defines the operation of 15.6ma BANs with other wireless systems (worst-case scenario) operating in the same frequency band. 15.6ma BANs support interference mitigation and higher reliability via FEC mechanisms.

The difference in the different class environments is the possibility of identifying the interferer system to apply prescribed interference mitigation techniques described in [36]. Hence, the transition between coexistence classes depends on interference detection, which is implementation dependent. Once an environment class is identified, the group coordinator shall start a procedure to transition to a new Class environment.

However, the transition to a new class environment depends on devices support the FEC configurations and interference estimation, which are implementation dependent.

Coexistence environments Class 1, Class 2 and Class 4 shall be supported by the identification of their respective beacons.

4.3.3 Network Topologies

The std IEEE802.15.6-2012 supports network topologies of star and one-hop star. This revision IEEE802.15.6ma supports topologies including star, star plus one and two hops; for instant star: coordinator(hub) and multiple nodes such as sensors and actuators, and one and two relay nodes. In a one-hop star BAN, frame exchanges are to occur directly between nodes and the coordinator of the BAN. In a two-hop extended star BAN, the coordinator and a node are to exchange frames optionally via a relay-capable node.

This revision considers compatibility with legacy 802.15.6-2012 devices but does not include mechanisms to ensure backwards compatibility and means to ensure enhanced dependability in new 802-15-6ma devices in precise channel models and coexistence classes in HBAN, VBAN, and their mixed-use cases.

This revision builds upon existing mechanisms in the standard to support sharing of spectrum with overlapping services, and introduces several new mechanisms described in sections that follow.

5 Overview of 802.15.6ma Multiple Ultra-Wide BANs Coexistence

The IEEE 802.15.6 Task Group is developing a new UWB-PHY that operates in the designated UWB frequency bands between 3.1 and 10.6 GHz. To assure that such PHY will provide reasonable performance when operating near other wireless devices, the 802.15.6ma Task Group has adopted the policies and conventions of the IEEE 802.19 Coexistence Technical Advisory Group (TAG).

5.1 Operating Frequency Bands

The allocated frequency bands for the 802.15.6ma UWB PHY are the frequency range from 3.1 GHz to 10.6 GHz. The actual spectrum used varies by region. The allocated frequency bands for the 802.15.6ma UWB PHY are shown in table 1.

5.2 Modulation Parameters

The 802.15.6ma UWB PHY has modulation parameters in the different frequency bands in impulse radio type of UWB modulation such as on-off keying, pulse positioning modulation (PPM), time hopping referred in subclause 9.1.4 of IEEE802.15.6ma draft [14].

5.3 Coexistence Mechanisms

The proposed revision draft IEEE802.15.6ma provides several mechanisms that enhance coexistence of its UWB PHYs with other wireless devices operating in the same spectrum. The revision includes the same mechanisms of legacy standard IEEE802.15.6 such as:

- Very low transmit power.
- Low duty cycle
- Modulation
- Time hopping
- Error-Control with FEC and Hybrid ARQ corresponding to combination between packet QoS levels and coexistence classes
- Clear channel assessment (CCA)
- Active and inactive frames periods
- Local regulations that may require detect-and-avoid (DAA) techniques.

Moreover, the revision IEEE802.15.6ma proposes new coexistence mechanisms in MAC and PHY.

- Control and data channels (CDC) in UWB bands defined to enhance dependability in classified coexistence by controlling access to avoid contention in MAC.
- Coordinator-to-coordinator (C2C) negotiation among coexisting multiple BANs to identify the number of full and partial overlaid BANs and to synchronize a group of overlaid BANs.
- C2C ranging among coexisting multiple BANs to monitor and identify transition of coexisting status.

- Appropriate sets of preamble sequences assigned to coexisting multiple BANs with less cross correlation [37]

5.3.1 Coexistence Scenarios and Analysis for Ultra-Wide Band PHY

The proposed revision draft IEEE802.15.6ma provides several mechanisms that enhance coexistence of its UWB PHYs with other wireless devices operating in the same spectrum. The revision includes the same mechanisms of legacy standard IEEE802.15.6 and additional mechanisms in MAC and PHY.

5.3.1.1 Coexistence Class States Transition

The standard's revision supports BANs operating with high reliability (coexistence class 0) and coexisting in dense environments with intra-interference and inter-interference (coexistence class 1 to 7) where each class is defined in Table 4. Figure 1 shows the state transition between classes of coexistence environments defined in Table 4.

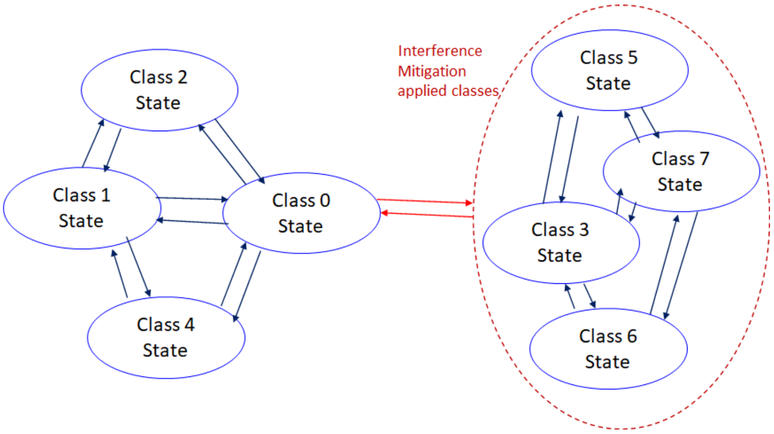


Figure 1; Diagram of state transitions for coexistence class environments.

- The standard's revision focuses on the dependability mechanisms for a single HBAN or VBAN (Class 0) and the scenario with multiple HBANs or VBANS (Class 1).

- Class 2 supports compatibility with legacy BANs (IEEE 802.15.6-2012 Std).

- Class 4 supports coexistence with other IEEE 802.15 UWB Stds, and amendments such as 15.4, 15.8, 15.4z, and 4ab, via the PHY and MAC specification.

- Classes 3, 5, 6, and 7 support coexistence with other wireless systems via interference mitigation technology at the receiver side.

5.3.2 Coexistence mechanisms for Ultra-Wide Band

The following subclauses 5.3.2.1 – 5.3.2.6 are the same as the std IEEE802-15-6-2012 and new mechanism in the revision IEEE802.15.6ma is described in subclause 5.3.2.7.

5.3.2.1 Low transmit power.

The UWB PHYs operate under strict regulations for unlicensed UWB devices worldwide. The least restrictive regulations for UWB are available under the Federal Communications Commission (FCC) rules, US 47 CFR Part 15, subpart F. Under these rules, the highest allowable limit for UWB emissions is based on an effective isotropically radiated power (EIRP) of –41.3 dBm/MHz. Other future UWB regulations in other regions will be likely at this same level or even lower.

Under these limits, the allowable transmit power for a train of pulses with spectrum $G(f)$, whose power spectral density (PSD) is centered at frequency f_c and whose amplitude has been set to 1 for convenience is given by

$$P_{\mathrm{EIRP}} = 10\,\mathrm{Log}_{10}\left[\left(\int_0^{\infty} G^2(f)\,df\right)10^{-41.3/10}\right] \qquad \text{(a)}$$

If all available spectrum in a 10 dB point bandwidth of 500 MHz were perfectly filled with the maximum allowed signal PSD, the total $P_{\mathrm{EIRP}}^{\max}$ = -14.3 dBm. This value represents the maximum possible EIRP limit for a UWB signal under this particular regulation and setting.

The maximum allowable EIRP for a compliant pulse shape is found by computing Equation (a) and satisfies $P_{\mathrm{EIRP}} < P_{\mathrm{EIRP}}^{\max}$ assuming any channel in the frequency band plan.

This transmit power level is at or below the limits for unintentional emissions from other electrical or electronic devices. In addition, this power level value is less than the out-of-band emission limits for other unlicensed devices operating in designated bands such as the 2.4 GHz ISM or 5 GHz UNII bands.

Additionally, since this transmits power is spread over at least 500 MHz of bandwidth, the highest power in the operating bandwidth of a typical narrowband 20 MHz victim system is less than –28.29 dBm. These very low power levels emitted into the operating band of any potential victim system with this characteristic will reduce the likelihood that UWB devices might interfere with other narrowband systems.

5.3.2.2 Low duty cycle

The IR-UWB specifications of this revision IEEE802.15.6ma and its original standard IEEE802.15.6-2012 are tailored for applications with low power and low data rates with a constant duty cycle of 3% for all data rates. This makes IEEE 802.15.6 devices less likely to cause or be subject to interference by other standards.

On the other hand, at the MAC level, the maximum interference level to victim systems can be limited by controlling the duty cycle of packets or frames through active and inactive periods. The traffic can occur only in the active period. Victim systems are free of interference in the inactive period. The control of active and inactive periods is managed by the BAN coordinator(hub) and a given application.

The interference level is restricted by the ratio of active period to the active plus inactive period. The possible packet collision in the active period can be mitigated by

1) Contention Access mechanism, IR-UWB can implement packet sense as the same as CSMA-CA mechanism. FM-UWB can implement carrier sense of a narrowband system in IEEE802.15.6-2012.

2) Slotted Aloha with channel indicator. This channel-dependent Aloha sets transmission probability related with channel's quality, which can be obtained through listening to a beacon or preamble symbol from the hub by means of ED. The function to map channel quality to transmission probability is defined at application layer.

3) Limit the number of node devices through association.

4) Traffic shaping like a combination of short packet to large packet.

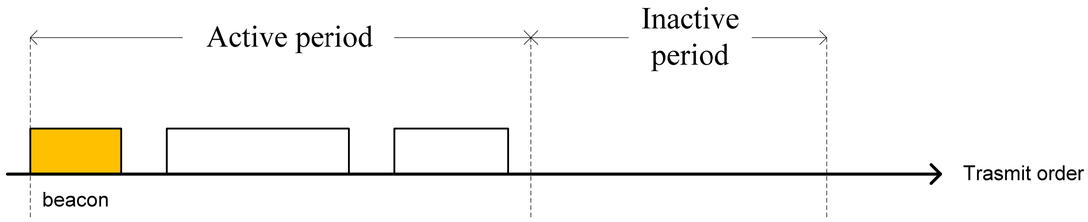


Figure 2—Concept of active and inactive periods

5.3.2.3 Modulation

The IR-UWB PHY has a high QoS mode in which differentially encoded BPSK or QPSK combined with differential detection are employed. This strategy is the best compromise between performance and complexity. Performance is better and more robust to interference than on-off modulation, but slightly more complex. Furthermore, the use of complaint chirp pulses opens the possibility of novel detection strategies that have been proof resilient against interference.

In IEEE802.15.6-2012, the FM-UWB PHY combines CP-2FSK modulation with wideband FM. The mandatory data rate is 250 kbps, the central frequency of CP-2FSK modulation is 1.5 MHz and bandwidth of 800 kHz, also known as subcarrier. Subsequently, the wideband FM signal has a transmission bandwidth given approximately by the Carlson's rule:

$$BW_{\mathrm{FM}} \approx (2\beta + 1) f_m \quad \text{(b)}$$

where β is the modulation index and f_m is the largest frequency component of the CP-2FSK signal. Hence, if f_m =1.9 MHz, then $BW_{\mathrm{FM}} \approx 500$ MHz for β =130.5.

The effect of spreading the data signal's bandwidth of 800 kHz to 500 MHz transmission bandwidth is similar to spread spectrum. This high processing gain of FM-UWB allows resilience against interference. On the other hand, a BAN hub with a FM-UWB radio must implement an IR-UWB radio as well. Thus, the hub has control of both UWB technologies and can enforce low interference between them.

5.3.2.4 Time hopping

A dynamic time hopping sequence ™ is generated by a linear feedback shift register (LFSR). A hub initializes such TM generator according to the Kasami or Ivanov sequence number used to form the synchronization header (SHR) [14]. There are 8 possible sequences. Hence, a different TH sequence can be associated for a different BAN. Simulation results show the performance under multiple BANs improves significantly.

5.3.2.5 Clear channel assessment

The receiver energy detection (ED) measurement for clear channel assessment (CCA) is an estimate of a (mostly) narrowband signal's power around its central frequency. It is meaningless when the signal's power is below the noise floor (ultra-wideband signal). No attempt is made to identify or decode signals on the channel.

The FM-UWB PHY can perform carrier sense of a narrowband system after FM demodulation by ED over a certain threshold. Carrier sense cannot be applied for IR-UWB as the signal power level is below the noise floor. However, a hub or coordinator with FM-UWB radio must implement an IR-UWB radio as well. Consequently, carrier sense by FM-UWB can be used for the IR-UWB radio as well.

The IR-UWB PHY can perform CCA by preamble detection. CCA shall report a busy medium upon detection of a synchronization symbol $\mathbf{S}_i$. Otherwise, slotted Aloha is employed.

5.3.2.6 Channal Coding

Forward error correction(FEC) with proper error detecting abd correcting channek codes corresponding to each combination of packet QoS levels and coexistence classes have been designed in Table 5.

Table 5; Error-Control with FEC and HARQ corresponding to combination between packet QoS levels and coexistence classes

Coexistence Class	0	1	2	3	4	5	6	7
QoS Level								
0	LDPC or BCC	LDPC or BCC	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)
1	LDPC or BCC	LDPC or BCC	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)
2	LDPC or BCC	LDPC or BCC	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)
3	LDPC or BCC	LDPC or BCC	LDPC or BCC	LDPC(in) & RS(\\\out)	LDPC(in) & RS(out)	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)
4	LDPC(in) & RS(out)	LDPC(in) & RS(out)	CFP/HARQ	LDPC(in) & RS(out)	LDPC(in) & RS(out)	LDPC or BCC	LDPC(in) & RS(out)	LDPC(in) & RS(out)
5	LDPC(in) & RS(out)	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ	CFP/HARQ	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ
6	LDPC(in) & RS(out)	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ	CFP/HARQ	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ
7	LDPC(in) & RS(out)	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ	CFP/HARQ	LDPC(in) & RS(out)	CFP/HARQ	CFP/HARQ

BCC means BMinary Convlutional Code, LDPC(in) & RS(out) does concatenated code with LDPC as inner code and RS(Reed-Solomon) code as outer code, and CFP/HARQ does HARQ(Hybrid ARQ) in CFP. HARQ is otional.

The high QoS mode employs a more powerful channel code based on the shortened BCH (126,63) in case of a packet is found in error by CRC-16 error detection mechanism. Thus, the BANs under high QoS mode are more robust to interference.

5.3.2.7 New Coexistence Scenarios

The revision IEEE802.15.6ma proposes new coexistence mechanisms in MAC and PHY. Control and data channels (CDC) with UWB bands defined to enhance dependability in classified coexistence by controlling access to avoid contention in MAC. In a basic case of CDC with single UWB band, control and data channels are in the same UWB band. In optional case of CDC, control and data channels are in different UWB bands to avoid interference in control coexistence among UWB systems. The detail coexistence mechanism is described in MAC function of the draft [4] and its concept has been presented in the document [35].

During CCA and beacon periods, a BAN coordinator may analyze the type of synchronization preamble detected from a 15.6ma, 15.6, or 15.4 system.

In Figure 1, the state transition probabilities are approximated in consecutive superframes. Furthermore, the duration of the CAP and CFP are determined by the type of QoS associated with every superframe, or group frame and available resources to avoid congestion.

The revision supports BANs operating with high reliability in dense environments coexisting with intra-interference and inter-interference due to other wireless systems in the same frequency band. Figure 1 shows state transition among several classes of coexistence environment defined in Table 4.

As shown in Figure 1, coexistence environment classes 0, 1, 2, and 4 perform enhanced dependability. These classes are relatively easy to detect as those involve 15.6ma, 15.6, or 15.4 radios, where all the specification in PHY and MAC such as type of beacons, superframe structure, MAC frame and functions are known, and compatible. MAC function of the revision can detect overlaid coexisting legacy and new BANs and IEEE802.15.4 UWB WSNs by the known specification of PHY and MAC. Particularly class 1 of multiple new BANs coexistence can use with new schemes such as

- Control and data channels in UWB bands defined to enhance dependability in classified coexistence by controlling access to avoid contention in MAC.
- Coordinator-to-coordinator (C2C) negotiation among coexisting multiple BANs to identify the number of full and partial overlaid BANs and to synchronize a group of overlaid BANs.
- C2C ranging among coexisting multiple BANs to monitor and identify transition of coexisting status.

Coexistence environment classes 3, 5, 6, and 7 where every specification may not be known. Coordinators of new BANs may detect unknown coexisting systems overlapped frequency bands with a new BAN and suppress or cancel interference from other radios with digital filters and antenna directivity in time, frequency, and space domains. Then class 3,5, and 6 may result in classes 0, 1, 2, and 4.

5.3.3 Coexistence performance analysis for Ultra-Wide Band

This revision IEEE802.15.6ma new BAN uses only UWB PHY while IEEE802.15.6-2012 legacy BAN uses NB, HBC, and UWB PHY.

5.3.3.1 Performance analysis of coexisting UWB systems according to their distance

A theoretical analysis of packet error ratio is described in Figure 3 according to distance between two UWB Human BANs (HBANs).

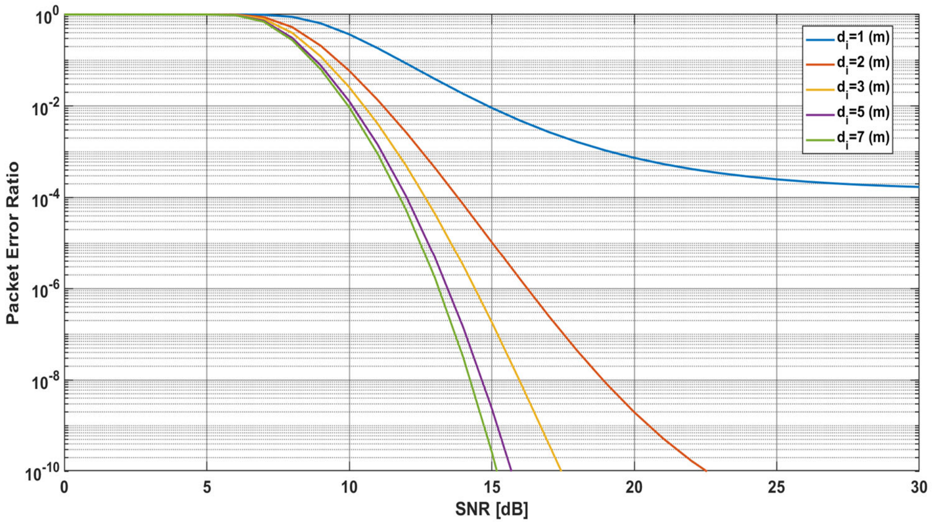


Figure 3—Packet Error Rate (PER) of Coexisting Two HBANs as a Funcgion of SNR according to Distance between HBANs

Fig3 shows PER in a case that $N_i = 1$, B = 499.2 (MHz), $S_t = -41.3$ (dBm/MHz), $L_{\mathrm{PSDU}} = 1296$ (bit), Path loss of CM3 (S4 and S5, $d = 0.25$ (m)) and HBAN to HBAN interference (S6.2, $d_i = 1,2,3,5,7$ (m)),

$\mathrm{PER} \triangleq 1-(1-P_b)^{L_{\mathrm{PSDU}}}$ (Packet error ratio, L_{PSDU}: PSDU length (bit))

$P_b = Q\left(\sqrt{2\gamma}\right)$ (Bit error probability, BPSK)

$\gamma = \frac{P_r}{N_0 B + N_i P_I}$ (P_r: Received power, N_0: Noise spectral density, B: Bandwidth, N_0: Number of interferences, P_I: Each received interference power)

$\mathrm{SNR} = 10\log_{10}\frac{P_r}{N_0 B}$ (dB)

$P_r = S_t + 10\log_{10} B - P_{\mathrm{loss,CM3}}(d)$ (dBm) (S_t: Transmission spectral density, $P_{\mathrm{loss,CM3}}(d)$: Path loss in CM3, d: sensor to hub distance (mm))

$P_I = S_t + 10\log_{10} B - P_{\mathrm{loss,HtoH}}(d_i)$ (dBm) ($P_{\mathrm{loss,HtoH}}(d_i)$: Path loss in HBAN to HBAN LOS case, d_i: Hub to hub distance (mm))

* $P_{\mathrm{loss,CM3}}(d)$ and $P_{\mathrm{loss,HtoH}}(d_i)$ are referred from IEEE 802.15-22-0519-07-006a, May 2024

This figure shows that over 2m separation between twn UWB BANs can perform PER less than 10^{-4}.

5.3.3.2 Performance analysis according to the number of coexisting UWB BANs

Coexistence of multiple 802.15.6 UWB BANs and other UWB systems such as IEEE 802.15.4a, 4z, 4ab is a key issue in providing enhanced dependability. The proposed draft 15,6ma is revised from legacy BAN 15.6-2012 to manage to synchronize coexisting BANs and other UWB systems by new coexistence mechanism in PHY and MAC such as CDC, C2C and MAC function [14]. However, the management of coexistence may not always successful.

In multiple 15.6 UWB BANs and 15.4 UWB systems coexistence, fundamental performance analysis is described in cases that the management of coexistence is successful to synchronize most of UWB BANs but a few of others UWB systems is not synchronized. In the analysis coordinators or hubs of UWB BANs and others control synchronization to avoid packet collision and contention but some of coexisting UWB systems are not under control.

Figure 4 shows packet error rate (PER) in an example of four out of five UWB BANs are synchronized but one UWB BANs is not under control. This shows a case that some of the BANs are not 15.6ma BANs but legacy BANs and 15.4 UWB systems.

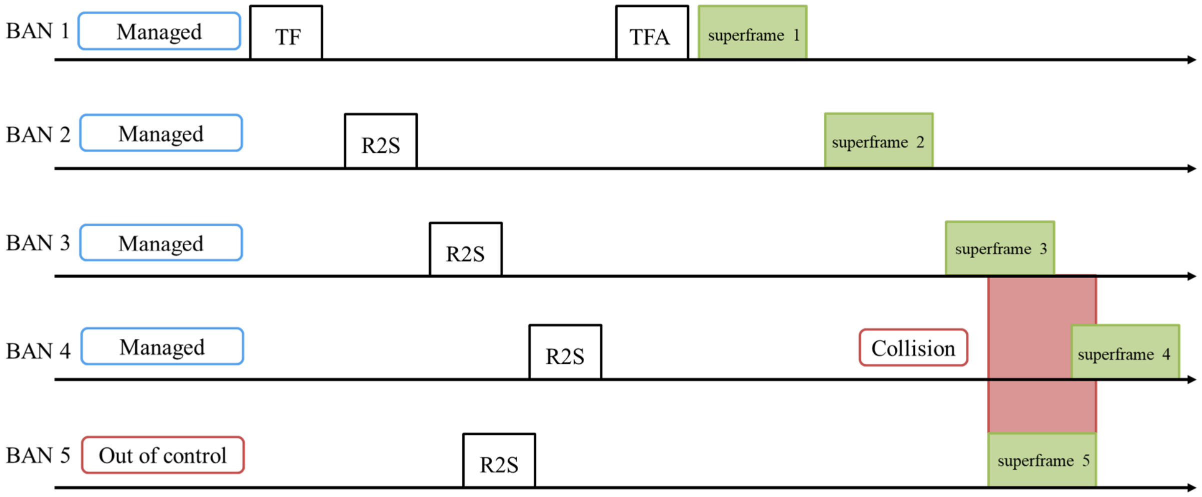
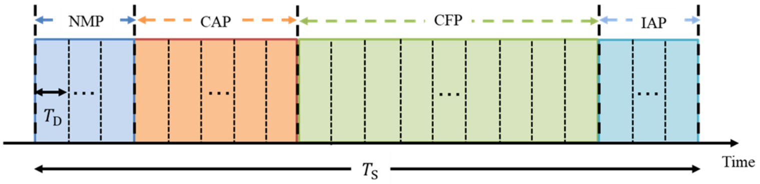


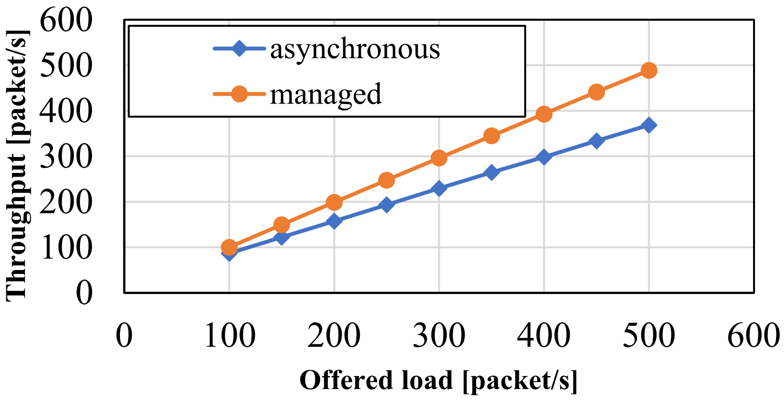
Figure 4— A Case of Four UWB BANs Synchronized but One Asynchronized out of Coexisting Five UWB BANs

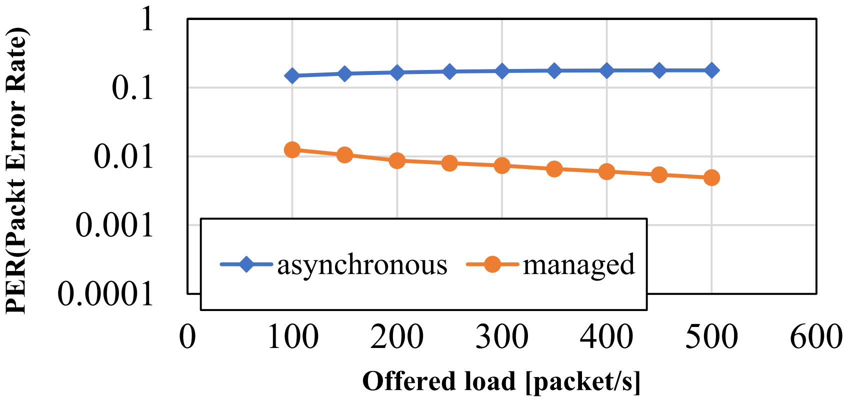
Table 6 shows simulation parameters in the case of Fig,4.

Table 6; Simulation Parameters in Five BANs Coexistence

T_S	4 ms	Number of BANs	5
T_D	40 µs	Number of Nodes (/BAN)	5
Number of superframes	250	Maximum number of retransmission (CFP) times	5
Number of NMP slots	5	Maximum number of retransmission (CAP) times	5
Number of CFP slots	60	Maximum number of random waiting slots (CAP)	10
Number of CAP slots	30	Normal packet (CFP)	Poisson distribution
Number of IAP slots	5	Normal packet (CAP)	Poisson distribution
Gap	0 ~ 499	Packet length	2000 bit







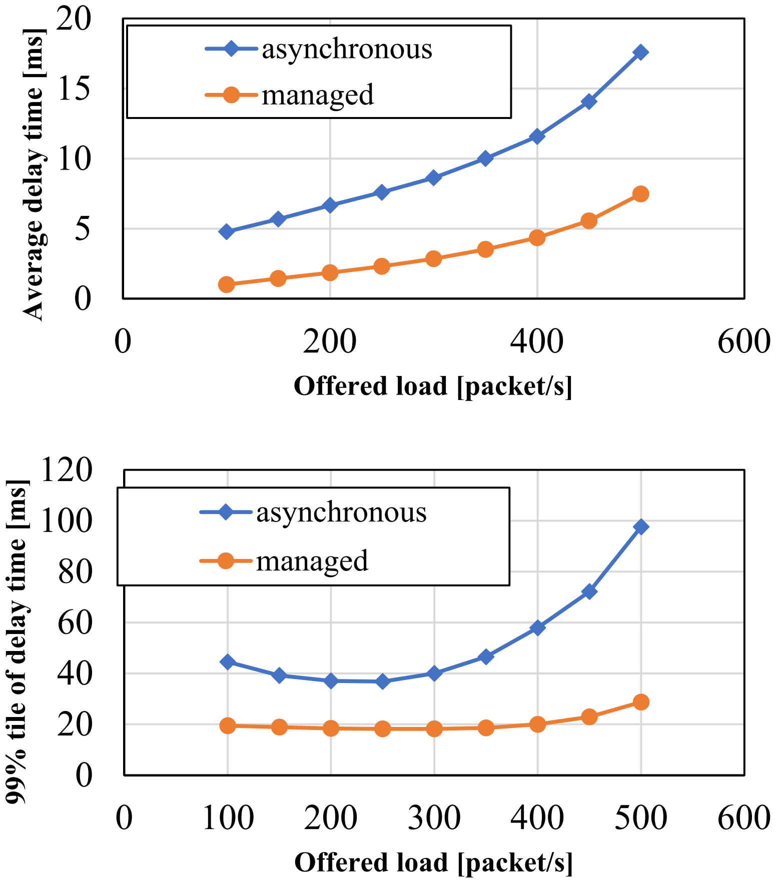


Figure 5— Throughput, PER, Average Delay Time, and 99%title of Delay Time in Case of Four UWB BANs Synchronized but One Asynchronized out of Coexisting Five UWB BANs

Fig. 5 shows simulation results of average system performance in the case of Fig,4 with parameters of Table 5 This result confirms that this case can perform technical requirement.

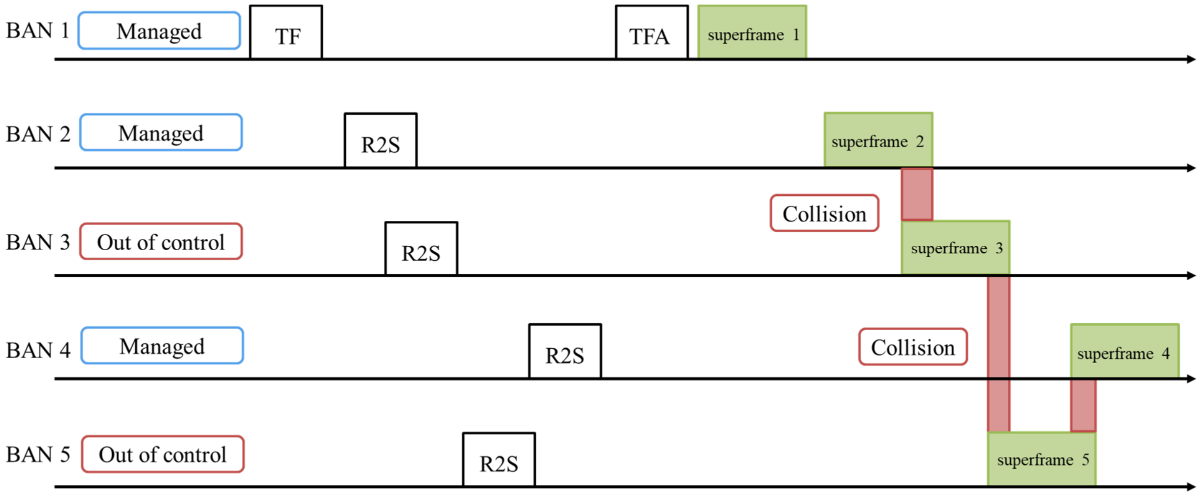
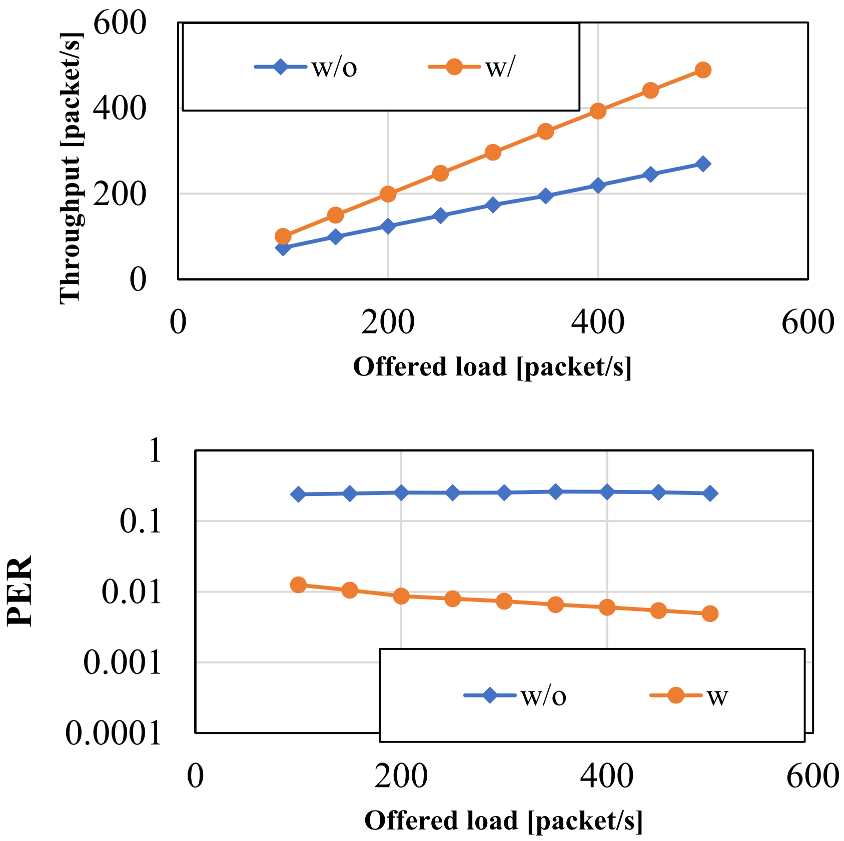


Figure 5— A Case of Three UWB BANs Synchronized but Two Asynchronized out of Coexisting Five UWB BANs

Fig.6 shows simulation result in the case of Fig,5 with the same parameters of Table 5.



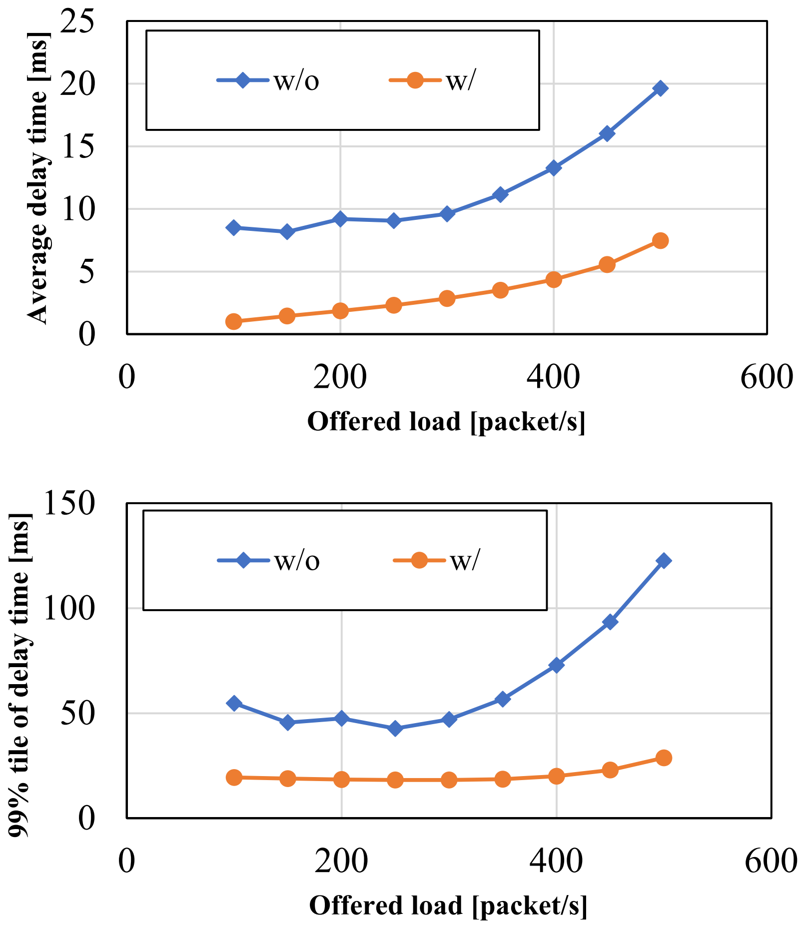


Figure 6— Throughput, PER, Average Delay Time, and 99%title of Delay Time in Case of Three UWB BANs Synchronized but Two Asynchronized out of Coexisting Five UWB BANs

Fig. 6 shows simulation results of average system performance in the case of Fig,5 with parameters of Table 5 These results show that at least four out of five coexisting BANs should be synchronized by the coexistence mechanism to safisfy the technical requirement.

5.3.3.3 Performance analysis according to the covering range of coexisting UWB BANs

(1) In the packet errors analysis in 5.3.3.2, all packets which have contentions were counted as packet errors. However, even if packets have contentions, some packets can be correctly received according to SINR.

(2) In this packet errors analysis in 5.3.3.3, packet errors may be counted more carefully considering SINR in case of contention.

While tn the packet error analysis in 5.3.3.2, layout of BANs was assumed pentagon, in new packet error analysis, layout of BANs are randomly distributed in a circle.

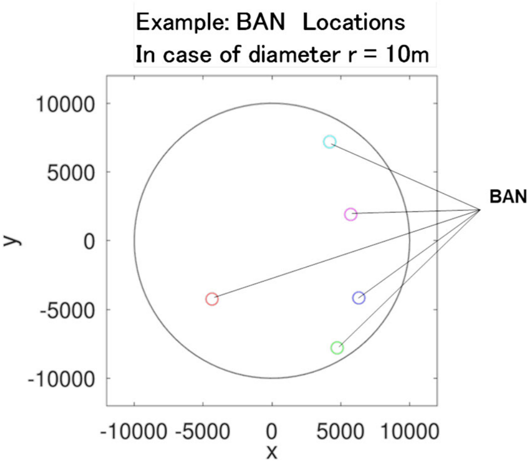
Number of BANs can be more flexibly changeable. Diameter of the circle can be flexibly changeable. Random geographical distribution has been calculated according to the flowing manner.

BAN location (x,y) can be calculated in case of circle with diameter d

$$\begin{cases} x = r\sin\theta \\ y = r\cos\theta \end{cases} \quad 0 \le \theta \le 2\pi, 0 \le r \le d$$

- r and Θ can be calculated uniform random numbers in (0,1
- BAN location can be derived

$$\begin{cases} \theta = 2\pi u \\ r = \sqrt{d^2 v} \end{cases}$$


Example: BAN Locations
In case of diameter r = 10m

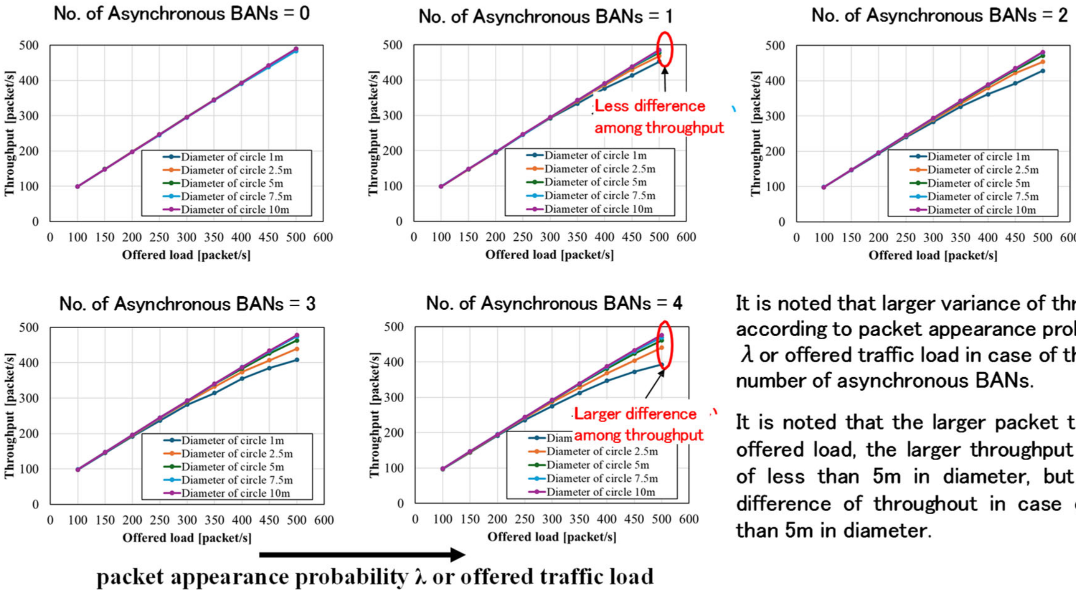
Simulation Specifications:

Diameter of circle inside which BANs are distributed	1.0, 2.5, 5.0, 7.5, 10
Number of Asynchronous BANS	0, 1, 2, 3, 4
Number of Simulation Trials	100

Where assumed that layout of BANs were reset every simulation trial, Asynchronous BANs were randomly selected in each simulation trial.

SimulationSpecifications

T_S	4 ms	Number of BANs	5
T_D	40 µs	Number of Nodes (/BAN)	5
Number of superframes	250	Maximum number of retransmission (CFP) times	5
Number of NMP slots	5	Maximum number of retransmission (CAP) times	5
Number of CFP slots	60	Maximum number of random waiting slots (CAP)	10
Number of CAP slots	30	Normal packet (CFP)	Poisson distribution
Number of IAP slots	5	Normal packet (CAP)	Poisson distribution
Gap	0 ~ 499	Packet length	2000 bit
Tx power	-10 dBm		


No. of Asynchronous BANs = 0

No. of Asynchronous BANs = 1

No. of Asynchronous BANs = 2

No. of Asynchronous BANs = 3

No. of Asynchronous BANs = 4

Less difference among throughput

Larger difference among throughput

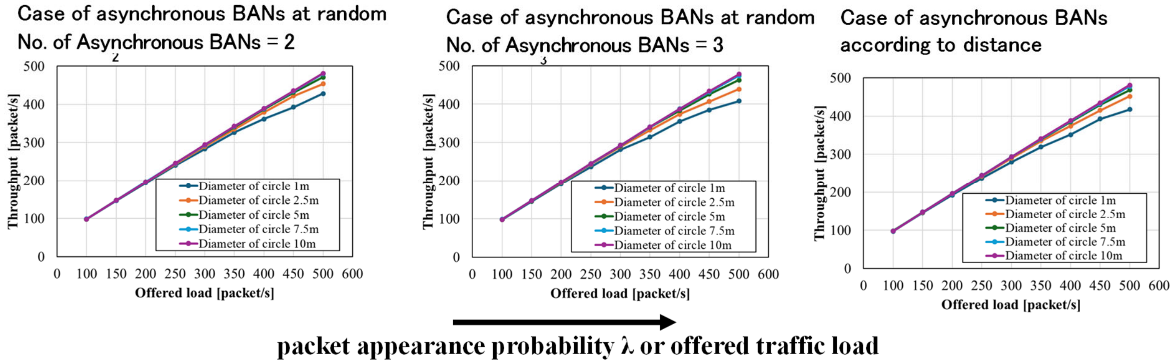
It is noted that larger variance of throughput according to packet appearance probability λ or offered traffic load in case of the larger number of asynchronous BANs.

It is noted that the larger packet traffic or offered load, the larger throughput in case of less than 5m in diameter, but a little difference of throughout in case of more than 5m in diameter.

packet appearance probability λ or offered traffic load

Figure 7. Throughput versus Packet appearance probabilityλor offered traffic load in cases of different no. of coexisting BANs and covering geographical range

These simulations are performed in cases of different decision rule of packet error rate and geographical distribution of coexisting BANs, The simulation confirms that throughput is quite dependent on the number of asynchronous BANs. In case of coexisting BANs closer than 5m, throughput may significantly degraded as increase of asynchronous BANs. However, in case of BANs far than 5m, throughput is a little different even different number of asynchronous BANs, This simulations confirm that if a group BAN coordinator can control the number of asynchronized coexisting BANs less than 5 within covering range of 5m in diameter, then packet error rate can be under controlled and result in permissible throughput in a certain range of packet traffic or offered load. The covering range 5m is dependent on transmission power of each BAN. This simulation is meaningful in a sense that the new standard MAC of IEEE802.15,6ma is robust against some non under controlled coexisting BANs,


Case of asynchronous BANs at random
No. of Asynchronous BANs = 2

Case of asynchronous BANs at random
No. of Asynchronous BANs = 3

Case of asynchronous BANs
according to distance

packet appearance probability λ or offered traffic load

Figure 8. Throughput versus Packet appearance probabilityλor offered traffic load in cases of different no. of coexisting BANs and covering geographical range

5.3.4 Assignment of Approproate Sets of Preamble Sequences to Coexisting Multiple BANs

Before C2C communication and ranging, all coordinators of coexisting multiple BANs with overlaid communication range should be synchronized each other. Otherwise, C2C ranging based on TOA or TDOA and C2C communication cannot be accomplished. To carry out stable initial acquisition and synchronization tracking, preamble sequences of beacons can be applied for correlation detection between the same preamble sequences in a received beacon from neighboring coordinator and a local receiver in a target BAN coordinator. Figure 9 illustrates success and error in acquisition. Essentially peaks beyond the predetermined threshold in an output of correlator are detected to sliding correlation procedure. The figure of lefthand side shows successful acquisition because autocorrelation peak is good enough larger than cross correlation peaks while that of righthand side shows error because cross correlation peaks are larger than autocorrelation peaks. Therefore, selection of preamble sequences assigned to neighboring BANs is essentially important for initial acquisition and synchronization tracking [37].

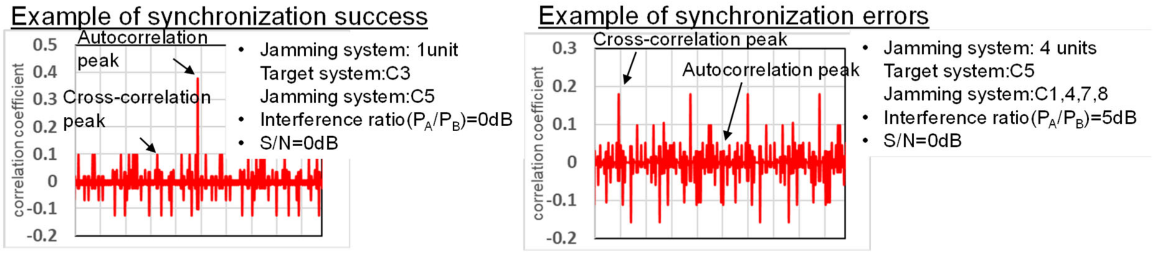


Fig.9 Synchronization Success and Error Corresponding to Relationship between Peaks of Auto Correlation of the Same Preamble Sequences and that of Cross Correlation of Different Preamble Sequences

By using UWB hardware modules, it has been confirmed that setting different preamble sequences help to reduce the interference in hardware experiment in a practical use case. Figure 10 shows an example of experiment to purpose low frame error rate(FER) of synchronization in the case of appropriate pair of preamble sequences assigned. Each VBAN consists of one node and one coordinator. Communication between the coordinator and the node in VBANs A and B is carried out simultaneously. Confirm the interference impact on VBAN A's communication from VBAN B and verse virsa.

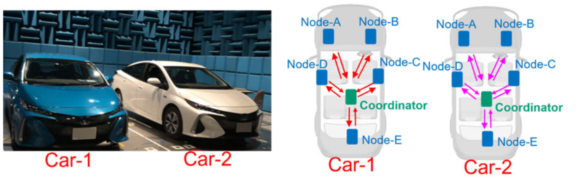


Fig.10 Co-located two Cars of which Wireless Harness Based on UWB-VBAN of IEEE802.15.6ma

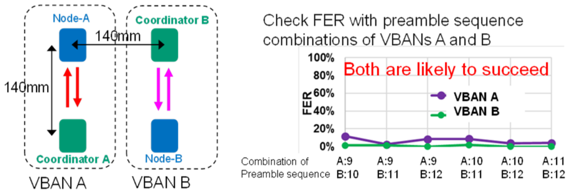


Fig. 11 Frame Error Rate of Synchronization in the Case of Co-located Two VBANs in Hardware Experiment

5.3.4.1 Evaluation Using Computer Simulations for Class 1 of Coexisting Multiple UWB-BANs

Simulations have confirmed that it is possible to achieve error-free frame synchronization even in the presence of interference from coexisting BANs and a noise by using appropriate preamble sequences and have demonstrated the interference reduction effect. This simulation adopted such a model that only one pair of a coordinator and a node can access a channel in each time slot. Check for frame synchronization errors in the target system or BAN when a coexisting jamming system or BAN with a different preamble sequence interferes to the target system or BAN. In simulation, a model of co-located two VBANs in Figure 12 and perfect frame synchronization in Figure 13 have been assumed. Table 5 shows simulation specification.

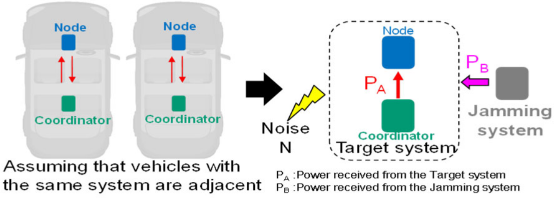


Fig. 12 Assumed Model of Co-located Two BANs in Computer Simulation

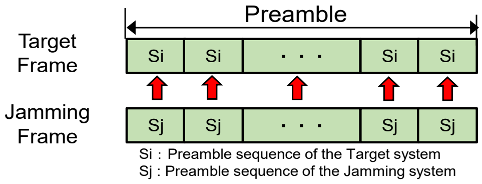


Fig. 13 Assumed Synchronized Frame in Simulation

A synchronization frame error is counted if summation of all cross-correlation among preamble sequences and noise in each time slot exceeds beyond the autocorrelation peak of preamble sequence of target system in the output of correlator in a target system as right figure in Fig.10. All of sets of preamble sequences specified as main/optional in standard P802.15.6ma listed in table 6 were examined in simulation.

(1) Case 1: Combinations of preamble sequences (only one jamming system: 1unit):

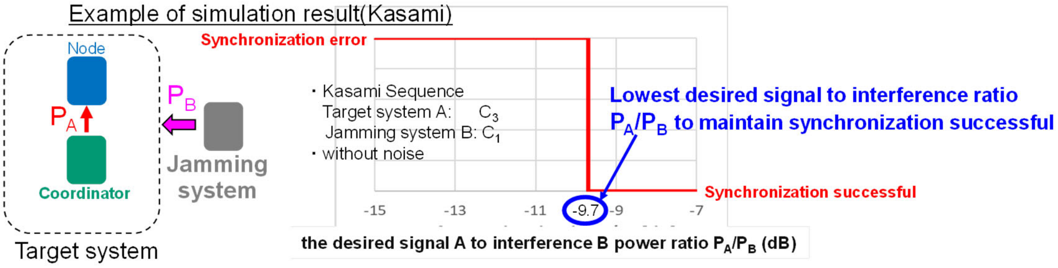


Fig. 14 Lowest Desired Signal A to Interference B Power Ratio P_A/P_B to Maintain Successful Synchronization in Coexisting 2 BANs Case

Using 1 unit of the jamming system, the superiority of the combination of preamble sequence is compared by simulation. All the combinations of preamble sequences are selected in the same family with of the same length while combination of Kasami and Ipatov sequence families is not the subject of this study. Simulation examed all combinations among preamble sequences for target and jamming systems. According to the desired signal A to interference B power ratio P_A/P_B, it is tested whether frame synchronization succeeds or fails to derive such a lowest desired signal to interference ratio P_A/P_B that frame synchronization can be maintained for all the combination among sequences. It is assumed in this simulation that there is no noise in order to evaluate only the superiority of combination of preamble sequence.

Simulation results are shown in Figure 15 and Table 7 for family of Kasami sequences and in Figure 16 and Table 8 for family of Ipatov sequences.

(a) Appropriate Pairs of Kasami Sequences

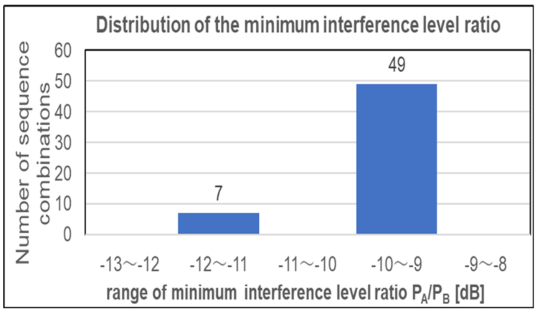


Fig.15 Results of Interference Level Ratio(Kasami)

Table 7 Best Ranking of Pairs of Kasami Sequences

Rank	Combination of preamble sequence [Target / Jamming]	Lowest desired signal to interference ratio P_A/P_B
1	$[C_1/C_2]$ $[C_1/C_3]$ $[C_1/C_4]$ $[C_1/C_5]$ $[C_1/C_6]$ $[C_1/C_7]$ $[C_1/C_8]$	-11.3 dB
2	$[C_2/C_1]$ $[C_2/C_3]$ $[C_2/C_4]$ $[C_2/C_5]$ $[C_2/C_6]$ $[C_2/C_7]$ $[C_2/C_8]$ $[C_3/C_1]$ $[C_3/C_2]$ $[C_3/C_4]$ $[C_3/C_5]$ $[C_3/C_6]$ $[C_3/C_7]$ $[C_3/C_8]$ $[C_4/C_1]$ $[C_4/C_2]$ $[C_4/C_3]$ $[C_4/C_5]$ $[C_4/C_6]$ $[C_4/C_7]$ $[C_4/C_8]$ $[C_5/C_1]$ $[C_5/C_2]$ $[C_5/C_3]$ $[C_5/C_4]$ $[C_5/C_6]$ $[C_5/C_7]$ $[C_5/C_8]$ $[C_6/C_1]$ $[C_6/C_2]$ $[C_6/C_3]$ $[C_6/C_4]$ $[C_6/C_5]$ $[C_6/C_7]$ $[C_6/C_8]$ $[C_7/C_1]$ $[C_7/C_2]$ $[C_7/C_3]$ $[C_7/C_4]$ $[C_7/C_5]$ $[C_7/C_6]$ $[C_7/C_8]$ $[C_8/C_1]$ $[C_8/C_2]$ $[C_8/C_3]$ $[C_8/C_4]$ $[C_8/C_5]$ $[C_8/C_6]$ $[C_8/C_7]$	-9.7dB

(b) Appropriate Pairs of Ipatov Sequences

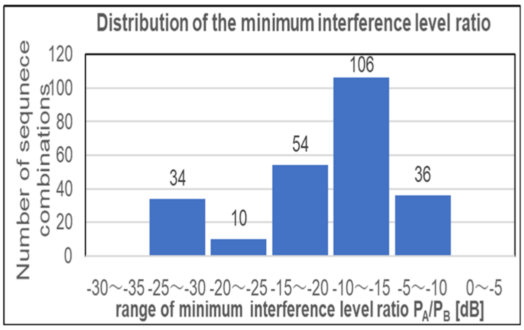


Fig.16 Results of Interference Level Ratio(Ipatov)

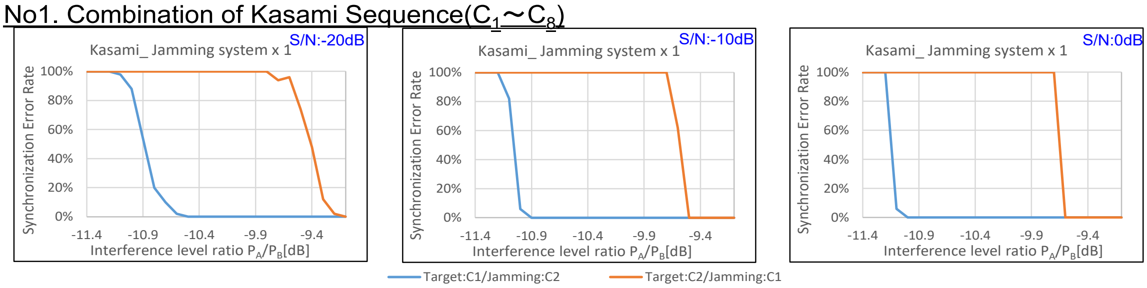
Table 8 Best Ranking of Pairs of Ipatov Sequences

Rank	Combination of preamble sequence [Target / Jamming]	Lowest desired signal to interference ratio P_A/P_B
1	$[C_9/C_{11}]$ $[C_{11}/C_9]$ $[C_{10}/C_{12}]$ $[C_{12}/C_{10}]$ $[C_{11}/C_{12}]$ $[C_{12}/C_{11}]$ $[C_{11}/C_{14}]$ $[C_{14}/C_{11}]$ $[C_{11}/C_{23}]$ $[C_{23}/C_{11}]$ $[C_{12}/C_{15}]$ $[C_{15}/C_{12}]$ $[C_{13}/C_{16}]$ $[C_{16}/C_{13}]$ $[C_{14}/C_{16}]$ $[C_{16}/C_{24}]$ $[C_{15}/C_{24}]$ $[C_{24}/C_{15}]$ $[C_{16}/C_{17}]$ $[C_{17}/C_{16}]$ $[C_{16}/C_{23}]$ $[C_{23}/C_{16}]$ $[C_{17}/C_{19}]$ $[C_{19}/C_{17}]$ $[C_{18}/C_{20}]$ $[C_{20}/C_{18}]$ $[C_{18}/C_{23}]$ $[C_{23}/C_{18}]$ $[C_{22}/C_{24}]$ $[C_{24}/C_{22}]$	-29.8 dB
2	$[C_{13}/C_{17}]$ $[C_{17}/C_{13}]$	-27.9dB
3	$[C_{10}/C_{24}]$ $[C_{24}/C_{10}]$	-26.3dB
39	$[C_{15}/C_{21}]$ $[C_{21}/C_{15}]$	-5.6dB

It is confirmed that by choosing appropriate sets of preamble sequences, it is possible to maintain synchronize successful even in the presence of a jamming system. In particular, the family of Ipatov sequences has larger margin of interference from coexisting BANs if a high rank of combination of sequences [target/jamming] in the above tables 7 and 8.

Figure 17 shows difference among pairs of sequences in required desired signal to interference power ratio P_A/P_B. Selecting the appropriate set or high rank combination of preamble sequence, it is possible to synchronize even in the presence of a jamming system. The high rank of combination of Ipatov sequence achieves the best synchronization performance.

No1. Combination of Kasami Sequence(C_1～C_8)



No2. Combination of Ipatov Sequence(C_9～C_{24})

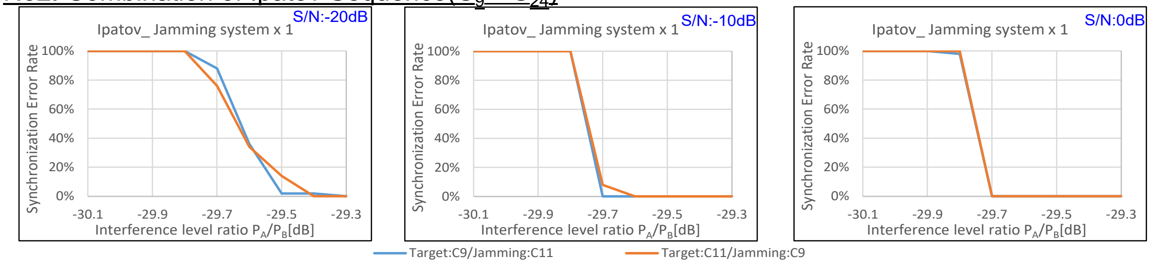


Fig.17 Difference in Required Desired Signal A to Interference B Power Ratio P_A/P_B to Maintain Successful Synchronization According to S/N in Case of Two VBANs Coexisting

(2) Case 2: Combinations of preamble sequence (4 jamming systems for target one)

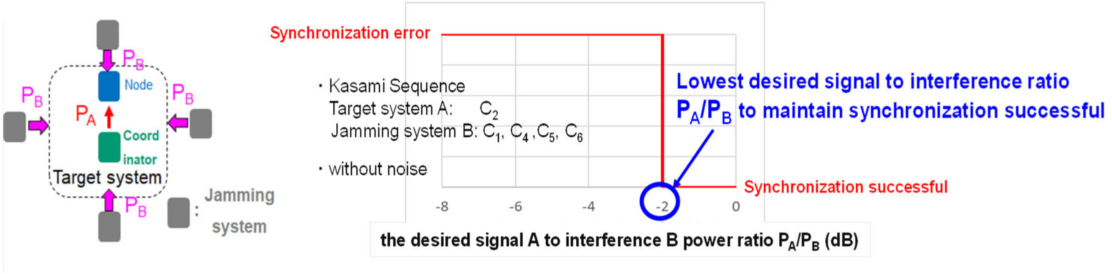


Fig. 18 Lowest Desired Signal A to Interference B Power Ratio P_A/P_B to Maintain Successful Synchronization in Coexisting 5 VBANs Case

Using 4 units of the jamming system, the superiority of the combination of preamble sequence is compared by simulation. All the combinations of preamble sequences are selected in the same family with of the same length while combination of Kasami and Ipatov sequence families is not the subject of this study. It was examined for all combinations among preamble sequences for target and jamming systems.

Simulation results are shown in Figure 19 and Table 9 for family of Kasami sequences and in Figure 20 and Table 10 for family of Ipatov sequences.

(a) Appropriate Sets of Kasami Sequences

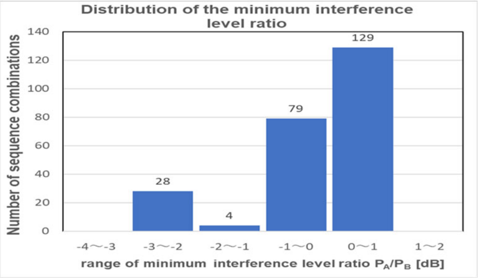
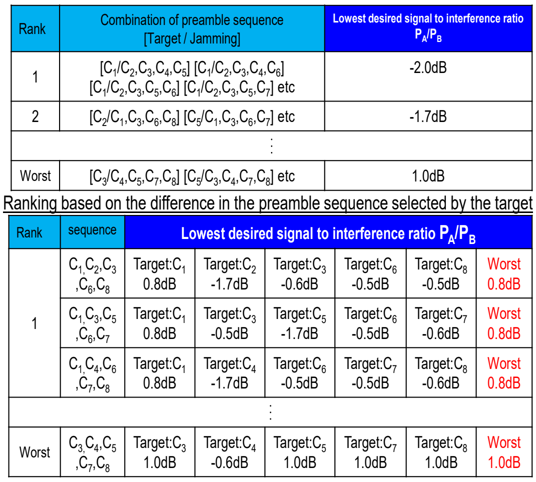


Fig.19 Results of Interference Level Ratio(Kasami)

Table 9 Best Ranking of Pairs of Kasami Sequences



Rank	Combination of preamble sequence [Target / Jamming]	Lowest desired signal to interference ratio P_A/P_B
1	$[C_1/C_2,C_3,C_4,C_5]$ $[C_1/C_2,C_3,C_4,C_6]$ $[C_1/C_2,C_3,C_5,C_6]$ $[C_1/C_2,C_3,C_5,C_7]$ etc	-2.0dB
2	$[C_2/C_1,C_3,C_6,C_8]$ $[C_5/C_1,C_3,C_6,C_7]$ etc	-1.7dB
⋮		
Worst	$[C_3/C_4,C_5,C_7,C_8]$ $[C_5/C_3,C_4,C_7,C_8]$ etc	1.0dB

Ranking based on the difference in the preamble sequence selected by the target

Rank	sequence	Lowest desired signal to interference ratio P_A/P_B					
1	C_1,C_2,C_3,C_6,C_8	Target:C_1 0.8dB	Target:C_2 -1.7dB	Target:C_3 -0.6dB	Target:C_6 -0.5dB	Target:C_8 -0.5dB	Worst 0.8dB
	C_1,C_3,C_5,C_6,C_7	Target:C_1 0.8dB	Target:C_3 -0.5dB	Target:C_5 -1.7dB	Target:C_6 -0.5dB	Target:C_7 -0.6dB	Worst 0.8dB
	C_1,C_4,C_6,C_7,C_8	Target:C_1 0.8dB	Target:C_4 -1.7dB	Target:C_6 -0.5dB	Target:C_7 -0.5dB	Target:C_8 -0.6dB	Worst 0.8dB
⋮							
Worst	C_3,C_4,C_5,C_7,C_8	Target:C_3 1.0dB	Target:C_4 -0.6dB	Target:C_5 1.0dB	Target:C_7 1.0dB	Target:C_8 1.0dB	Worst 1.0dB

(b) Appropriate Sets of Ipatov Sequences

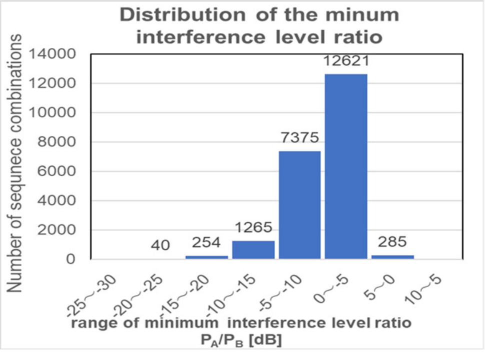
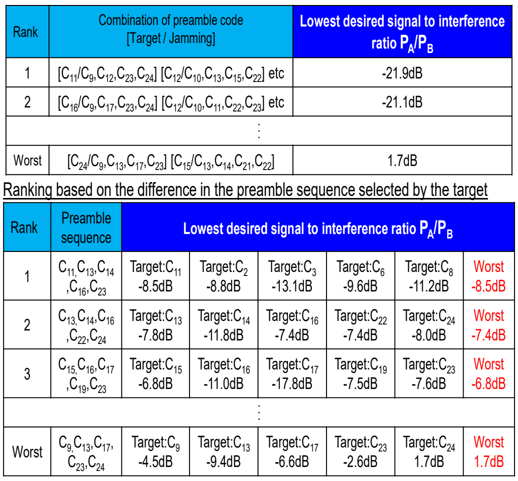


Fig.20 Results of Interference Level Ratio(Ipatov)

Table10 Best Ranking of Pairs of Ipatov Sequences



Rank	Combination of preamble code [Target / Jamming]	Lowest desired signal to interference ratio P_A/P_B
1	$[C_{11}/C_9,C_{12},C_{23},C_{24}]$ $[C_{12}/C_{10},C_{13},C_{15},C_{22}]$ etc	-21.9dB
2	$[C_{16}/C_9,C_{17},C_{23},C_{24}]$ $[C_{12}/C_{10},C_{11},C_{22},C_{23}]$ etc	-21.1dB
⋮		
Worst	$[C_{24}/C_9,C_{13},C_{17},C_{23}]$ $[C_{15}/C_{13},C_{14},C_{21},C_{22}]$	1.7dB

Ranking based on the difference in the preamble sequence selected by the target

Rank	Preamble sequence	Lowest desired signal to interference ratio P_A/P_B					
1	$C_{11},C_{13},C_{14},C_{16},C_{23}$	Target:C_{11} -8.5dB	Target:C_2 -8.8dB	Target:C_3 -13.1dB	Target:C_6 -9.6dB	Target:C_8 -11.2dB	Worst -8.5dB
2	$C_{13},C_{14},C_{16},C_{22},C_{24}$	Target:C_{13} -7.8dB	Target:C_{14} -11.8dB	Target:C_{16} -7.4dB	Target:C_{22} -7.4dB	Target:C_{24} -8.0dB	Worst -7.4dB
3	$C_{15},C_{16},C_{17},C_{19},C_{23}$	Target:C_{15} -6.8dB	Target:C_{16} -11.0dB	Target:C_{17} -17.8dB	Target:C_{19} -7.5dB	Target:C_{23} -7.6dB	Worst -6.8dB
⋮							
Worst	$C_9,C_{13},C_{17},C_{23},C_{24}$	Target:C_9 -4.5dB	Target:C_{13} -9.4dB	Target:C_{17} -6.6dB	Target:C_{23} -2.6dB	Target:C_{24} 1.7dB	Worst 1.7dB

Even with four jamming systems or BANs, coexistence is possible in the Ipatov sequence by selecting an appropriate set or high rank combination of preamble sequences, even when the interference level is higher than the system level.

5.3.4.2 Summary of Computer Simulations for Class 1 of Coexisting Multiple UWB-BANs

(1) Case with one adjacent vehicle or coexisting BAN

Synchronization during simultaneous communication is possible using either the Kasami sequence or the Ipatov sequence if an appropriate set or high rank combination of sequences, where the Ipatov sequence has better performance. When the Ipatov sequence family is selected, the FER performance is depending on the combination of the preamble sequences, so it is necessary to assign an appropriate set or high rank combination of sequences to coexisting BANs. It is desirable for the group BAN coordinator to assign an appropriate set of preamble sequences based on the high rank combination of preamble sequences.

(2) Case with four adjacent vehicle or coexisting BANs

The Kasami sequence family is not appropriate for 4 BANS because it cannot synchronize when the interference power received from adjacent vehicles is high. The Ipatov sequence allows synchronization during simultaneous communication by selecting an appropriate set of preamble sequences. The group BAN coordinator should assign appropriate preamble set of sequences based on the high rank of the preamble sequence combinations to be assigned to coexisting BANs.

5.4 IEEE Std 802.11-2007 (5 GHz) coexistence performance

The revision IEEE802.15.6ma and its original standard IEEE 802.15.6-2012 provide several mechanisms that enhance coexistence of its UWB PHYs with other wireless devices operating in the same spectrum. These mechanisms include:

- Very low transmit power.
- Low duty cycle
- Modulation
- Time hopping
- Error-Control with FEC and Hybrid ARQ corresponding to combination between packet QoS levels and coexistence classes
- Clear channel assessment (CCA)
- Active and inactive frames periods
- Local regulations that may require detect-and-avoid (DAA) techniques.

Coexistence sinario and system performance analysis are described in 5.3.

5.5 IEEE Std 802.15.4a-2007 (UWB) coexistence performance

The revision IEEE802.15.6ma and its original standard IEEE 802.15.6 provide several mechanisms that enhance coexistence of its UWB PHYs with other wireless devices operating in the same spectrum. These mechanisms include:

- Very low transmit power.
- Low duty cycle
- Modulation
- Time hopping
- Error-Control with FEC and Hybrid ARQ corresponding to combination between packet QoS levels and coexistence classes

- Clear channel assessment (CCA)
- Active and inactive frames periods
- Local regulations that may require detect-and-avoid (DAA) techniques.
- Coordinator-to-coordinator(C2C) communication for synchronize BANs.
- Ranging between coordinators of coexisting BANs

Coexistence scenario and system performance analysis are described in 5.3.

6 New 802.15.6ma and Legacy 802.15.6 Multiple Ultra-Wide BANs Coexistence; Class 2

6.1 Coexistence Mechanisms

As the same mechanism as Class 1 described in subclause 5.3, the proposed revision draft IEEE802.15.6ma provides several mechanisms that enhance coexistence of its UWB PHYs with legacy standard IEEE802.15.6 such as:

- Very low transmit power.
- Low duty cycle
- Modulation
- Time hopping
- Error-Control with FEC and Hybrid ARQ corresponding to combination between packet QoS levels and coexistence classes
- Clear channel assessment (CCA)
- Active and inactive frames periods
- Local regulations that may require detect-and-avoid (DAA) techniques.

Moreover, the revision IEEE802.15.6ma proposes new coexistence mechanisms in MAC and PHY.

- Control and data channels in UWB bands defined to enhance dependability in classified coexistence by controlling access to avoid contention in MAC.

  Since coordinators of new BANs can detect a beacon of coexisting legacy BAN and identify it as a legacy BAN using knowledge of its MAC address and formant.

- Coordinator-to-coordinator (C2C) negotiation among coexisting multiple legacy and new BANs to identify the number of full and partial overlaid BANs and to synchronize a group of overlaid BANs.

Coexistence scenario and system performance analysis are described in 5.3.

7 Other IEEE 802 Standards Occupying Same Frequency Bands as IEEE 802.15.6ma Ultra-Wide Band

This clause enumerates IEEE-compliant devices that are characterized in the document and devices that are not characterized for operation in proximity to IEEE 802.15.6ma devices.

IEEE Standards characterized for coexistence are as follows:

- IEEE Std 802.11-2007 (5 GHz)
- IEEE Std 802.11y-2008 (3 GHz)
- IEEE Std 802.11n-2009 (5 GHz)
- IEEE Std 802.16-2009 (below 11 GHz: primarily 3 GHz, 5-6 GHz)
- IEEE Std 802.15.4a-2007 (UWB band)
- IEEE Std 802.15.4z-2020 (UWB band)

Proposed IEEE standard characterized for coexistence is as follows:

- IEEE 802.15.4ab (UWB band)

7.1 802.11 Coexistence; Class 3

7.1.1 802.11 WLAN impact on 802.15.6ma UWB

The IEEE802.15.6 has been taken into account as the same as IEEE802.15.4 detailed in エラー! 参照元が見つかりません。-エラー! 参照元が見つかりません。 contain information, analysis and measurement based studies of coexistence between 802.15.6 UWB and 802.11 operating in overlapping channels. These show the potential for severe impacts on UWB operation from collocated 802.11 devices.

Thes studies show that physical separation is an effective mitigation technique. In some scenarios, separation of 100s of meters is required. In others, when used in conjunction with other coexistence mechanisms, separation on the order of 10 meters is sufficient. As a sole means of mitigating interference, physical separation is often not sufficient.

Due to the extreme difference in transmit power levels used by UWB and 802.11, the UWB signal at as little as 1m physical separation from the 802.11 device is below -90 dBm/MHz. This is substantially below any of the energy detect thresholds specified for 802.11 CCA. The 802.11 channel access will not detect and defer in the presence of a UWB signal. However, if the UWB transmission is substantially below 1ms in duration, the peak limit applies and the UWB peak may be -58 dBm at the receiver at 1m, and detection is possible.

In エラー! 参照元が見つかりません。 and エラー! 参照元が見つかりません。 offsetting in frequency by more than the UWB channel width is used and can be effective in mitigating interference risk. However, it is shown that out of band emissions of the RLAN system complying with the 802.11 standard can cause impactful interference with the UWB signal. These studies show in-band 802.11 can have a measurable impact on UWB with as much as 946 meters of physical separation.

In エラー! 参照元が見つかりません。 and エラー! 参照元が見つかりません。, it is shown that partial frequency offset can improve coexistence (both ways) significantly. These studies included use of SSBD to improve coexistence. In this scenario, the UWB device can detect transmissions from the 802.11 device, while the 802.11 device does not detect and defer in the presence of UWB signals. This one-way LBT is shown to improve coexistence performance. These studies also used frequency diversity in the UWB system, operating over multiple UWB channels. This is shown to improve coexistence performance also.

Further study of coexistence impacts is needed. In particular, the inability of 802.11 based devices to detect UWB creates an asymmetric situation, compromising simple techniques based on LBT. The results presented in the referenced studies suggest that effective coexistence is possible, with further study and development of new techniques holds promise.

7.1.2 802.15.6ma UWB impact on 802.11 WLAN

7.1.2.1 802.15.6ma UWB PHY impact on 802.11 WLAN

This revision (6ma) applies a low energy UWB PHY as the same as legacy 802.15.6-2012 with PHY layer parameters defined for non-coherent data communications for several coexistence strategies. The low energy UWB PHY strategies can be applied for mitigation of impact on 801.11 WLAN and on other communications occupying the same bands.

The use of Energy Detection (ED) afforded by the non-coherent receiver of the low energy UWB PHY allows for enhanced detection of non-UWB transmissions for enhanced mitigation of interference to other systems. Listen-before-talk (LBT) is easily implemented. In fact, the low energy UWB PHY is intended to be combined with the Spectrum Sensing Based Deferral (SSBD) mechanism. SSBD based CCA LBT provides the ability for the low energy UWB PHY to detect concurrent networks transmission and to delay its own transmission or switch center frequency to avoid interfering. A practical demonstration of the effectiveness of SSBD is described in the "SSBD enabled UWB radio coexistence with Wi-Fi 6e demo" document for the case of coexistence between 802.15.4ab with 802.11 WLAN [29] [30].

As described in Clause 6, this revision introduces new strategies for coexistence such as Control and Data Channels CDC) and Coordinator-to-Coordinator(C2C) negotiation. Before data transmission in data channel control channel keeps detecting beacons from coexisting radios in the overlaid frequency with new BANs. The above-mentioned ED and SSBD are performed in the control channel as a kind of cognitive sensing. Thus, a coordinator of BAN identifies class of coexistence described in Figure 1. In fact, this section's model is classes 3 and 7. When the BAN coordinator detects 802.11 WLAN, the BAN can apply DAA, LDC, and transmission power control (TPC) according to priority order defined by regulation or other manners.

In addition, C2C acts in total interference management of multiple coexisting BANs to 802.11 WLAN by exchanging information on overlaid radio propagation environment. This function is optional in manufactures for further enhanced dependability of 6ma BAN providing additional robustness and mitigation of interference.

The combination of the above-mentioned coexistence strategies will mitigate interference to both similar and dissimilar systems.

7.1.2.2 802.15.6ma HRP UWB PHY impact on 802.11 WLAN

HRP and LRP UWB PHYs impact on 802.11 WLAN systems is described in エラー! 参照元が見つかりません。. The summary is that due to the extreme difference in transmit power, interference from UWB is very unlikely. With free space loss, a separation distance of 1m reduces the UWB power spectral density at the receiver to less than -80 dBm, which is below the energy detect thresholds specified in 802.11, and below the minimum receiver sensitivity for most modulation and coding schemes and channel widths specified for the overlapping bands. Additionally, typical uses of UWB employ duty cycle below 5% (often much below).

In addition to the prior analysis, エラー! 参照元が見つかりません。 and エラー! 参照元が見つかりません。 include measurement-based studies of UWB impact on 802.11 operation. In these studies, a very unrealistic scenario was required to measure any impact from UWB on the 802.11 devices. A collection of UWB devices (12) operating within 0.33 meters of the 802.11ax AP, operating in continuous transmission mode and at maximum power spectral density, centered on the 802.11 channel, in the lab environment, could show a performance impact on the 802.11 link (from zero to 60 % reduction in throughput). Physical separation of more than 0.33 meters mitigated all impacts. Reducing to a more realistic transmission duty cycle mitigated impact. These studies also showed that within the very small sphere of impact, mitigation techniques such as partial channel frequency offset and/or SSBD reduced the impact to unobservable.

7.2 802.15.4 UWB Coexistence; Class 4

This section considers issues regarding coexistence between IEEE 802.15.6ma devices and IEEE 802.15.4 devices.

7.2.1 802.15.4 and 4ab UWB impact on 802.15.6ma UWB

As the same manner as described in 7.2.1, IEEE802.15.6ma has new strategies for sensing and detecting coexiting radio systems. Among UWB systems, the control channel of IEEE802.15.6ma is used to detect a beacon of coexisting UWB systems to avoid interference from other UWB systems as well as coexisting 6ma BANs. Using pre-knowledge of ready existing IEEE802.15 standards such as IEEE802.15.4a, 4z, and forthcoming 4ab, regarding MAC address, frame structure, beacon, preamble information etc., a type of IEEE802.15 standards is identified. The control channel of IEEE802.15.6ma is applied to reduce interference from 802.15.4 to 15.6ma.

Particularly 15.6ma has a common channel coding and decoding of LDPC code as 15.4ab for 0-3 QoS levels of packets and 4-7 QoS levels as inner code of concatenated coding, so a 15.6ma receiver can decode 4ab packets.

7.2.2 802.15.6ma UWB impact on 802.15.4 and 4ab UWB

As above described in 7.2.1, the control channel of 15.6ma is applied to identify 15.4 WSNs and avoid interference in PHY and contention in MAC.

8 Other non-IEEE 802 Standards Occupying Same Frequency Band as IEEE 802.15.6; Class 5, 6, and 7

There are no other IEEE 802 standards that occupy the same frequency bands as the IEEE 802.15.6ma but other standard such as ETSI SmartBAN UWB for implant BAN and other non-standard UWB and NB PHY systems.

8.1 Coexistence Class States Transition

The standard's revision supports BANs operating with high reliability (coexistence class 0) and coexisting in dense environments with intra-interference and inter-interference (coexistence class 1 to 7). Figure 1 shows the state transition between several classes of coexistence environments defined in Table 4.

- The standard's revision focuses on the dependability mechanisms for a single HBAN or VBAN (Class 0) and the scenario with multiple HBANs or VBANS (Class 1).

- Class 2 supports compatibility with legacy BANs (IEEE 802.15.6-2012 Std).

- Class 4 supports coexistence with other IEEE 802.15 UWB Stds, and amendments such as 15.4, 15.8, 15.4z, and 4ab, via the PHY and MAC specification.

- Classes 3, 5, 6, and 7 support coexistence with other wireless systems via interference mitigation technology at the receiver side.

During CCA and beacon periods, a BAN coordinator may analyze the type of synchronization preamble detected from a 15.6ma, 15.6, or 15.4 system.

In Figure 8-1, the state transition probabilities are approximated in consecutive superframes. Furthermore, the duration of the CAP and CFP are determined by the type of QoS associated with every superframe, or group frame and available resources to avoid congestion.

The revision supports BANs operating with high reliability in dense environments coexisting with intra-interference and inter-interference due to other wireless systems in the same frequency band. Figure 1 shows state transition among several classes of coexistence environment defined in Table 4.

As shown in Figure 1, coexistence environment classes 0, 1, 2, and 4 perform enhanced dependability. These classes are relatively easy to detect as those involve 15.6ma, 15.6, or 15.4 radios, whose beacons are known, and radios are compatible. Coexistence environment classes 3, 5, 6, and 7 deal with interference from other radios and result in classes 0, 1, 2, and 4.

9 Discussions and Conclusion

This document has presented an analysis of the coexistence between the IEEE 802.15.6ma and other IEEE 802 standards. In general, if PHY and MAC specification of any standard and non-standard networks are known, there is a manner of coexistence assurance by cognitive sensing with such a pre-knowledge, but it is out of range in this revision IEEE802.15.6ma and manufacturer option.