Doctoral Thesis
博士論文

Cognitive transmission control for UWB ad-hoc networks to co-exist with licensed cellular networks compliant to radio regulation

UWB アドホックネットワークの電波法に準拠して免許セルラーネットワークと共存するための環境適応型送信制御に関する研究

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Abstract

Microwave frequency band of ultra-wideband (UWB) wireless networks such as wireless body area network (BAN) overlaps with those of existing radio networks such as 3G, 4G, and 5G cellular networks, so coexistence strategies for UWB networks, i.e. secondary users in radio regulation should be considered to ensure the performance of such existing licensed wireless networks, i.e. primary users to satisfy radio regulation.

This study proposes our defined integrated terminal equipped with communication capability of both secondary UWB and primary cellular networks, which can retrieve channel state information of cellular network and also control transmission power of the UWB system. The proposed system can more accurately and precisely control the transmission power of the UWB network, so that its interference to the primary network can be kept below the permissible level of radio regulation while maximizing the communication opportunities of the UWB network at the same time, although a conventional UWB network has been simply switched off to avoid interference to a primary network in case of detecting a primary signal, so-called detection and avoidance (DAA).

The proposed integrated terminal can perform a gateway or common base station between primary cellular and secondary UWB ad-hoc networks to monitoring both giving and getting interference from UWB to cellular terminals. The proposed transmission power control scheme achieves cognitive and collaborative sensing of such interference in a channel.

Moreover, this study also proposes and investigates another control scheme, which is to control a length of spreading sequence of direct sequence UWB (DS-UWB) without spreading frequency bandwidth, in order to improve received UWB signal level with processing gain different from spreading gain.

These results can contribute to harmonization between primary and secondary co-existing wireless networks which lately UWB has been applied for iPhone 11 and other smartphones, automobile key-less entry system, and medical BAN while solving mutual interference problems.

あらまし

無線ボディエリアネットワーク (BAN) などの超広帯域 (UWB) 無線ネットワークが使用するマイクロ波の周波数帯域は、3G・4G・5G セルラーネットワークなどの既存の無線ネットワークが使用する帯域と重なるため、そのような既存の認可無線ネットワーク、すなわち 1 次利用のユーザーのパフォーマンスを保証するよう、無線規制による UWB ネットワークの共存対策が考慮されなければならない。

本研究では、セルラーネットワークのチャネル状態情報を取得し、UWB システムの送信電力を制御できる、2 次利用の UWB と 1 次利用のセルラーネットワークの両方の通信機能を備えた統合端末を定義し、提案する。従来の UWB ネットワークでは、1 次利用ネットワークからの信号を検出した場合、1 次利用ネットワークへの干渉を回避するために、単純に送信を止めることに対し、提案されたシステムは、統合端末が 1 次利用セルラーネットワークと 2 次利用 UWB ネットワークのゲートウェイ (共通基地局のような役割を果たす端末) となり、セルラー端末 (スマートフォンなど) が UWB 端末から受けている干渉レベルを統合端末経由で UWB 端末に伝え、送信電力を電波法上の許容範囲に抑えるよう、UWB ネットワークの送信電力をより正確かつ精密に制御できるため、1 次利用ネットワークへの干渉を無線規制の許容レベル未満に保ちながら、同時に UWB ネットワークの通信機会やスループットなどの通信性能を最大化できる。

統合端末は、1 次と 2 次利用ネットワークの中央制御基地局の役割を果たし、両ネットワークの複数端末による協調センシングにより、各端末ごとの被干渉と与干渉を正確に把握し、ネットワーク全体の干渉環境を認識するコグニティブ無線を具体化する。統合端末により両ネットワークの周辺端末間の電波干渉状況に関する環境を正確に把握し、双方の共用条件の制約下で UWB 無線ネットワークの性能を格段に改善できる環境適応型送信制御として、送信電力制御、さらに利用環境を広げる系列長制御により、電波法に準拠して 1 時利用処理利得を端末の動的変化の認識と送信適応制御方式を考案し、性能解析と最適化を導出する。

本研究成果は、最近の UWB 無線システムに対する電波法改正に伴い、iPhone 11 などのスマートフォンや自動車のキーレスエントリーのリレーアタック対策などの家電、自動車産業から、医療用 BAN などの医療業界に UWB 無線技術が広く応用される動向において、多様な UWB システムと免許システムを安全かつセキュアに合法的に運用することに、極めて有効である。

Chapter 1

Introduction

Recently, much attention has been drawn to ultra-wideband (UWB) wireless ad-hoc networks, which have advantages of high immunity to interference, high reliability from the ability to operate with low signal-to-noise ratios (SNR), simple transceiver architecture, high precision positioning, and large channel capacity [1]. Because of this, several international standards on UWB have been established, such as IEEE 802.15.6 Wireless Body Area Network (WBAN) and IEEE 802.15.4z Enhanced Impulse Radio UWB for Ranging and Positioning [2], and various UWB radio systems are being introduced in various fields, such as consumer products including iPhone 11 and iPhone 11 Pro, remote keyless system in automobiles [3], patient monitoring systems for medical care, and so on.

The UWB radio system operates at a ultra-wide microwave frequency band, as its name implies. Some part of the frequency bands overlap with the bands allocated to other existing radio systems such as 3G, 4G and 5G cellular networks [4]. Therefore, it is necessary to apply coexistence strategies to ensure the performance of the existing radio systems [5], [6].

Some of these coexistence strategies are embodied in the Radio Law, regulating the operation of UWB radio systems. For example, regulations in regions including Japan and the EU require UWB radio systems to be equipped with a Detect and Avoid (DAA) procedure. According to the DAA procedure, UWB radio systems must detect the presence of other systems in the overlapped frequency band before transmitting any signal, and limit their transmit power spectrum to -70 dBm/MHz if other systems are detected [7].

In Japan, this regulation included not only the transmission power limitation of UWB terminals, but also the prohibition of outdoor use, which has placed excessive restrictions on the UWB radio system and has been an obstacle to the popularization of the UWB radio system. However, through the recent revision of the Radio Law, UWB radio systems can be used outdoors, and in addition, a revision to widen the frequency band that can be used outdoors is in progress [8]. Therefore, it is expected that the restrictions imposed on the UWB radio system will be eased in the future, and through this, it is expected that the UWB radio system will be more actively introduced in a wider variety of fields, such as transportation, logistics, and retail, as well as communication, automobile, and medical care.

On the other hand, with the popularization of UWB radio systems, research and development of coexistence technologies with existing license systems, especially cellular systems, which have already been widely used, is urgently needed.

Various coexistence strategies have been studied [9] [10], and most of these works assume only carrier sensing of the coexisting primary licensed system. Then, UWB systems can have only a limited amount of information about the victim system, and vice versa. For example, in a conventional DAA, the UWB system simply detects if the signals of cellular network are present or not because the UWB system cannot accurately detect how much level of UWB transmitted power is interfering in cellular receivers, thus detection error occurs inevitably. This error may result in excessive interference which is not permissible for the cellular network, or deprivation of the communication opportunity for the UWB system.

In this paper, we define and propose the Integrated Terminal equipped with both secondary UWB and primary cellular systems like a cellular phone equipped Wi-Fi and Bluetooth as well as the cellular system, which can play a role of a gateway between primary cellular and secondary UWB networks to know more channel state and transmitting and receiving power balance between these networks. In fact, Apple released iPhone 11 and 11 Pro in which UWB RF device U1 has been equipped for localization of other terminals or handsets of iPhone 11 and 11 Pro. This means that our defined integrated terminal can be available in practice with minimum modification. The aim of this study is to control the transmission power of the UWB system accurately cognitive to co-existence of cellular and UWB systems, so that the UWB inference to the victim cellular system can be kept below the permissible level while maximizing the communication opportunities, i.e. throughput of the UWB system at the same time, by sharing the information of the interference received by the cellular system with the UWB system and control the transmission power of the UWB terminals in real time.

1.0.1 Thesis overview

This paper is organized as follows. In Chapter 2, the coexistence problem between UWB system and cellular system is described. The conventional coexistence strategies are also explained in this chapter. In Chapter 3, the concept of the Integrated Terminal is introduced. What is possible by using the Integrated Terminal is also explained in this chapter. In Chapter 4, the proposed transmit power control algorithm is presented, and the performance is evaluated in Chapter 5. In Chapter 6, the proposed spreading sequence length control algorithm is presented. Finally, Chapter 7 concludes this paper and provides directions of future works. The relations of these chapters can be found on Figure 1.1.

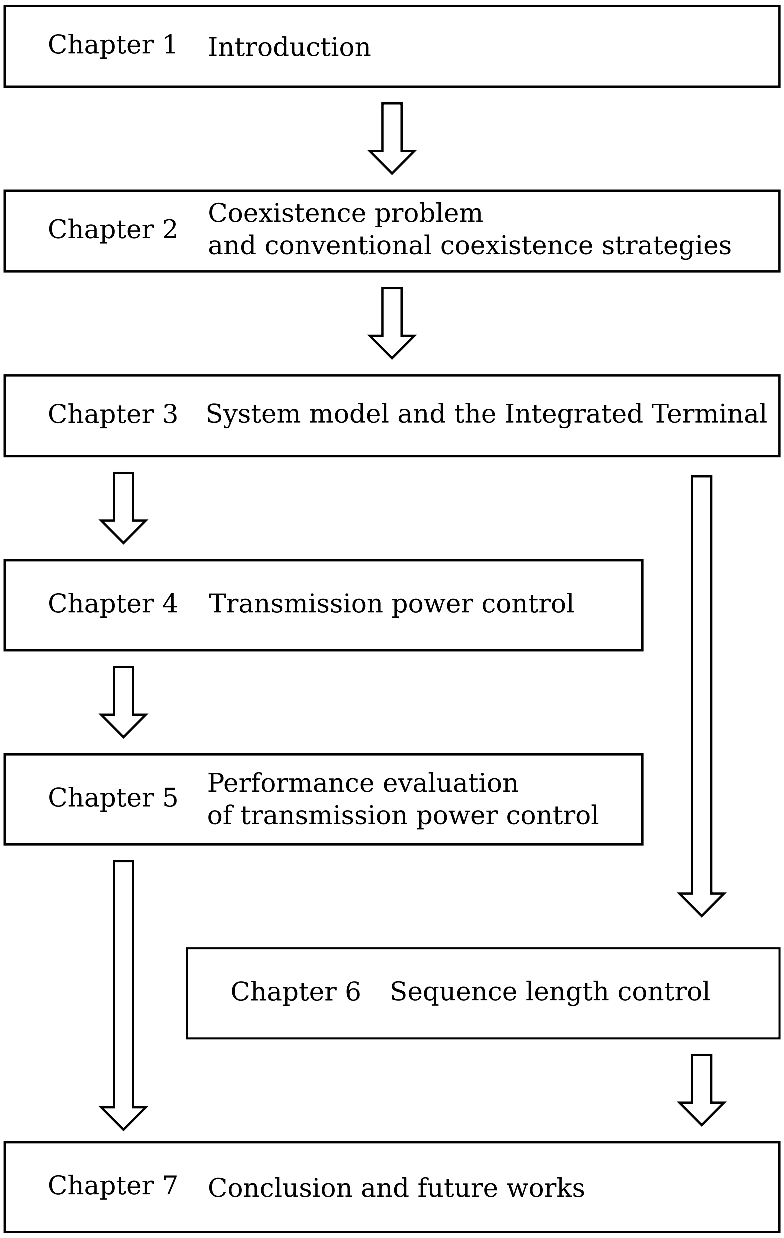

Figure 1.1 The structure of this thesis

Chapter 2

Coexistence problem and conventional coexistence strategies

In this chapter, the coexistence problem of ultra-wideband radio system and cellular network covered in this paper is explained.

2.1 Ultra-wideband radio system

Ultra-wideband (UWB) radio system, as its name implies, refers to a radio system that operates at an ultra-wide frequency band when compared to a conventional narrow-band or wide-band radio system. Here, the term ”ultra-wide” specifically means that the difference between the highest frequency and the lowest frequency exceeds 500 MHz (2–1), or the fractional bandwidth is equal to or greater than 20% (2–2), which is obtained by dividing the difference between this frequency by the center frequency. Figure 2.1 shows the conceptual diagram of the energy spectrum of UWB.

$$f_H - f_L \geq 500\,[\text{MHz}] \tag{2–1}$$

$$\frac{f_H - f_L}{f_c} \geq 0.2 \tag{2–2}$$

A UWB radio system has several characteristics because of its ultra-wide frequency band.

- high immunity to interference
  As illustrated in Figure 2.1, a UWB radio system distributes its signal energy over an ultra-wide frequency band. Therefore, the interference

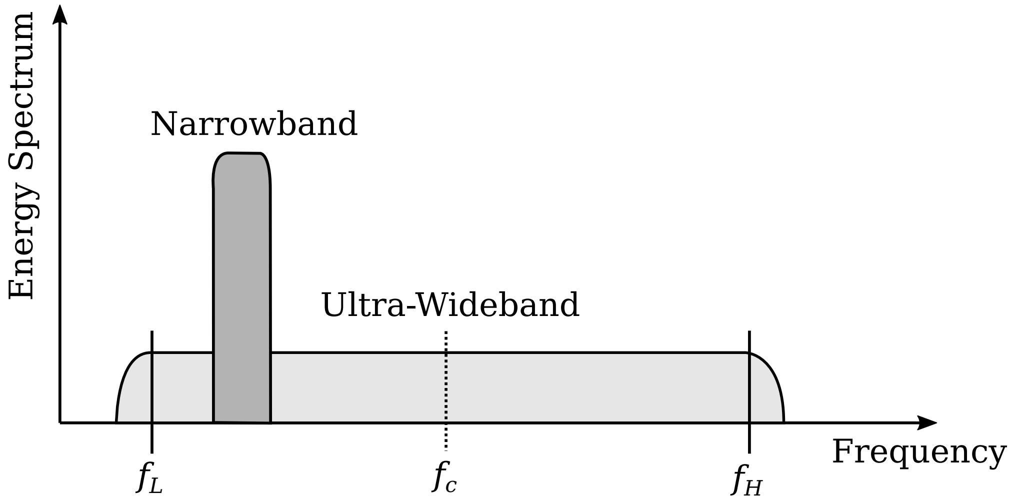

Figure 2.1 Energy spectrum of Ultra-wideband

caused by the UWB radio system is only as high as the noise level at the existing radio systems, and thus does not significantly degrade the quality of existing radio systems. In addition, since the interference caused by the existing radio system is limited to only a small part of the frequency band used by a UWB radio system, the UWB radio system is not significantly affected by the interference caused by the existing radio system too.

- large channel capacity

  As Shannon's theorem (2–3) shows, the channel capacity of a communication system is proportional to the bandwidth B. Therefore, in spite of the low energy spectrum and thus low signal-to-noise ratio, the large channel capacity can be realized by using an ultra-wide bandwidth.

$$C = B \log 2 \left(1 + \frac{S}{N}\right) \tag{2–3}$$

One of the common methods of implementing ultra-wideband radio is emitting signals in very short pulses in time, instead of using carrier wave. This kinds of UWB systems are called impulse radio UWB (IR-UWB). The conceptual diagram of the IR-UWB signal is shown in Figure 2.2.

In addition to the characteristics of UWB described above, the IR-UWB has following features.

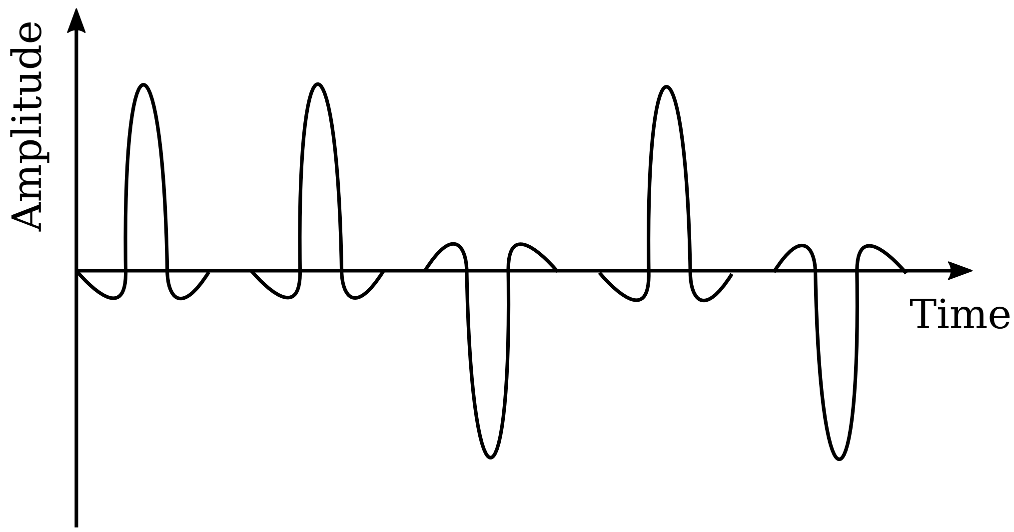

Figure 2.2 Example of IR-UWB signal

- high precision positioning
  An ultra-wide bandwidth in the frequency domain means that the signal using the bandwidth changes rapidly in the time domain. In IR-UWB, this results in a very short time duration of each pulses. Because of the short time duration, the high time resolution can be achieved, which is advantageous when used on ranging. This characteristic is useful not only for radar applications, but also for positioning application, because the high-precision positioning can be possible.

- simple transceiver architecture and low power consumption
  Generating and decoding the IR-UWB signal can be realized with a simple electric circuit, compared to that of the orthogonal frequency division multiplexing (OFDM) signal, because the circuit does not require Fourier transform or inverse Fourier transform processing. This makes it possible not only to manufacture the IR-UWB module at a low price, but also to lower the power consumption of the module.

Because of these characteristics, various UWB radio systems are expected to be introduced in various fields such as medical, transportation, logistics, retail, factory, and infrastructure as well as communication. There are international standards for UWB such as IEEE 802.15.6 Wireless Body Area Network (WBAN) which is targeted to medical use, and IEEE 802.15.4z Enhanced Impulse Radio UWB for Ranging and Positioning. Applications such as iPhone 11 and iPhone 11 Pro, remote keyless system in automobiles, and the medical body area network (BAN) are already available on the consumer market.

2.2 Coexistence problem and Cognitive Radio

Radio spectrum is a valuable and limited resource. As the internet of things (IoT) era approaching, where various devices have wireless communication feature, the lack of unoccupied frequency bands for novel radio system has emerged as a real problem. Cognitive radio (CR) technology that recognizes the surrounding environment and configures its own radio system parameters, has been proposed as a solution to this problem because it can reuse a frequency band allocated to existing radio systems. Especially, UWB radio systems have emerged as potential candidates for CR due to their low power spectral density thus low interference to existing radio systems.

According to the radio system and the right to use its frequency band, radio systems can be classified as follows:

- Primary systems have the rights to use their licensed frequency bands exclusively. Typical examples of the primary systems are cellular networks, broadcasting systems, satellite communications, and radio astronomy.
- Secondary systems "borrow" frequency bands already licensed to primary systems. A secondary system can use frequency bands when they are not used by their corresponding primary systems.

From a CR perspective [11], cellular networks are licensed primary systems, and therefore a secondary system, a UWB network, should not interfere with the communication of the cellular networks when reusing their frequency bands. However, because UWB radio systems transmit their own signals in the frequency bands which are used by other existing radio systems, if the UWB network spatially overlaps with the cellular network, the signal transmitted by the UWB terminal becomes an interference signal in the context of the cellular network terminal, inevitably degrading the performance of the cellular network. So, it is necessary to prepare strategies to coexist with cellular network. Conventional coexistence strategies that allow the UWB wireless system to communicate without interfering with the communication of the cellular system are explained in the next section.

2.3 Conventional coexistence strategies and the Radio Law

The rules for coexistence between such systems are established by the Radio Law. There are several regulations applied to a UWB system in order to protect the communication of cellular networks.

2.3.1 Spectrum mask

The most typical regulation is on the transmit power. UWB devices shall not emit radio waves above a specified spectral mask. The UWB spectrum masks applicable in Japan and the United States are shown in Figure 2.3 and Figure 2.4. Table 2.1 also describes the United States UWB spectrum mask in detail [12].

Because licensed radio systems in use vary from region to region, spectrum masks also vary from region to region. In the United States, the spectrum mask is also different for indoors and outdoors, while outdoor use of UWB is prohibited in Japan. In the case of Japan, it is noteworthy that in order to utilize the power spectrum density of -41.3 dBm/MHz in the 3.4-4.8 GHz band, an detect and avoid procedure is required.

Japanese regulation authority has been investigating technical requirements for UWB radio system that can enable outdoor use to correspond to the increasing demands of UWB radio system from various field, and to harmonize with other regions [8]. Details regarding this are summarized in the appendix A.

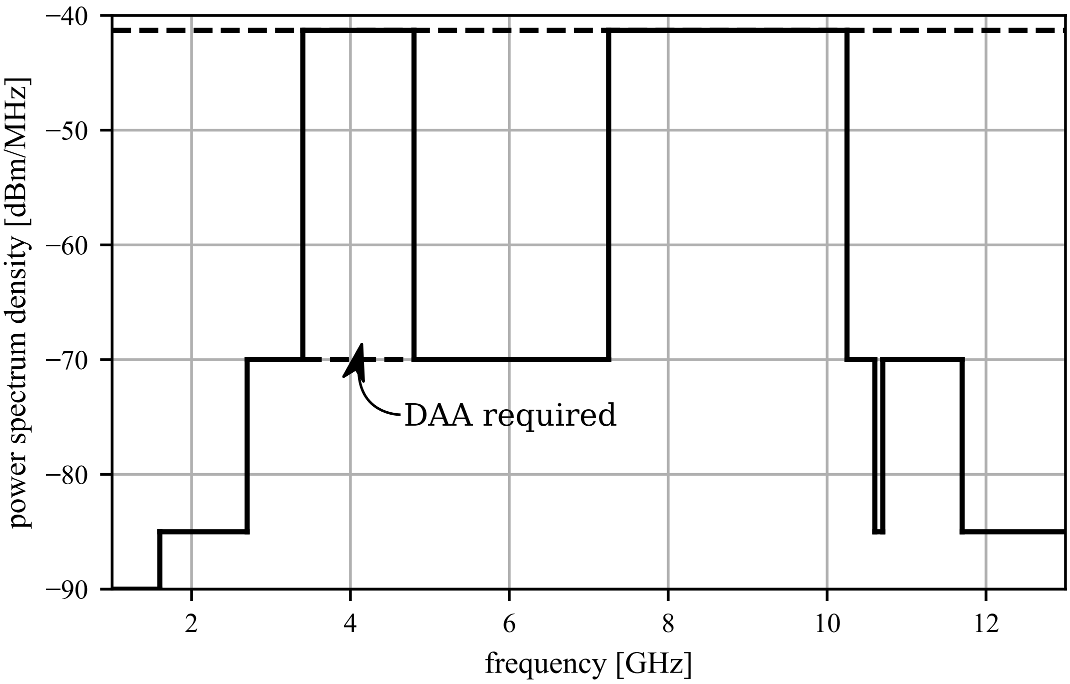

Figure 2.3 Japanese spectrum mask for UWB systems

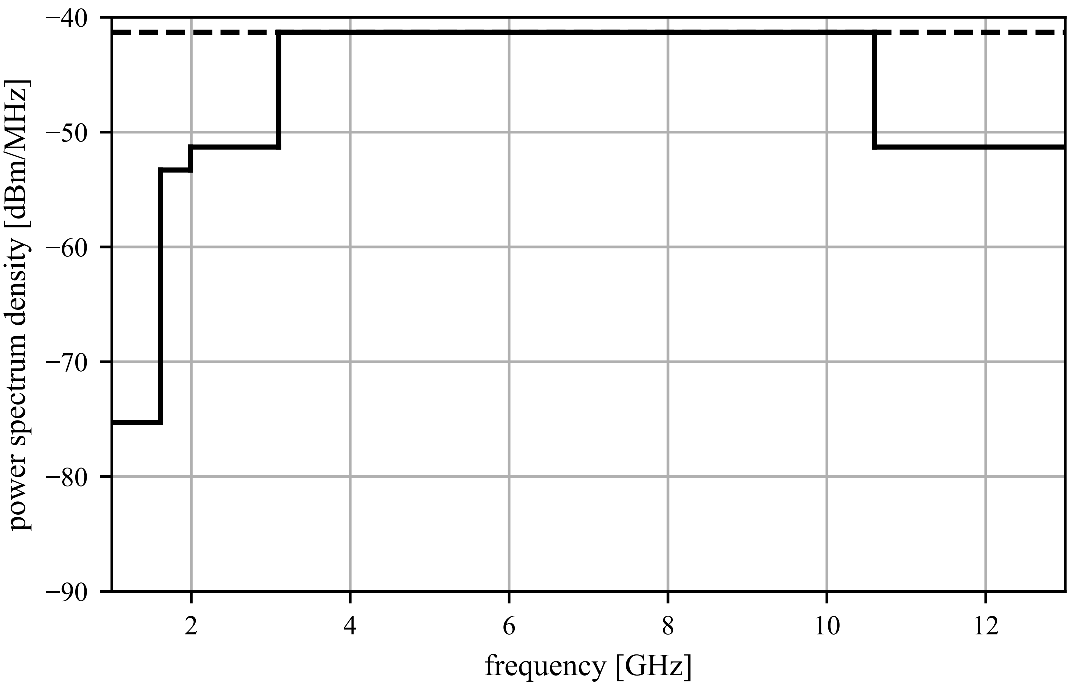

Figure 2.4 FCC spectrum mask for indoor UWB systems

2.3.2 Detect and avoid

It is required in many countries e.g. Japan to implement additional interference mitigation techniques such as detect and avoid (DAA) in order to exploit the maximum power of the spectrum mask described above. For example, in addition to the case of Japan described above, in Europe, if the DAA mitigation technique is not implemented, the maximum transmit power of a UWB terminal is limited to -70 dBm/MHz or -80 dBm/MHz rather than -41.3 dBm/MHz [7].

In the DAA procedure, the UWB system must listen to the channel before it emits radio waves. When a signal from the primary system is detected, it must either lower its transmit power to a level known to not interfere with the primary system, or abandon transmission.

2.3.3 Low duty cycle

Low duty cycle (LDC) has also been considered as another way to mitigate interference. LDC suppresses the interference to the primary system by shortening the time to for transmitting the signal.

2.4 Limitation of the conventional coexistence strategies

There are two discussions on the regulation of transmission power. First, this value may limit the communication opportunities of UWB more than necessary. Since the high frequency band used by UWB is sharply attenuated, if the terminal

Table 2.1 FCC spectrum mask for indoor UWB systems

Frequency [GHz]	EIRP [dBm/MHz]
0.96 - 1.61	-75.3
1.61 - 1.99	-53.3
1.99 - 3.10	-51.3
3.1 - 10.6	-41.3
Above 10.6	-51.3

of the primary system is not nearby, the higher transmission power of the UWB does not harm the primary network. On the other hand, if the primary terminal is nearby, applying this mask may not prevent damage to the primary network.

About DAA, Besides the discussion of whether the value of the upper power limit is appropriate, there are further discussions. First, the UWB system must have enough information about the primary system in order to detect the primary system with sufficient accuracy, which may require decoding some of the signal of the primary system. This not only cancel out the advantages of the UWB system such as simplicity and low power consumption, but also imposes a heavy burden on implementing it. Moreover, since the primary system also uses transmit power control (TPC) —in 3G, CDMA —it is difficult to find a reliable algorithm that controls the interference from the UWB system with the detected primary system signal. To avoid this problem, conventional DAA algorithms attempt to detect pilot signals transmitted at a constant power from the base station, but since pilot signals are supposed to be received at most locations where the cellular system is deployed, the DAA procedure will also determine that the channel is occupied by the primary system at such locations. The DAA procedure cannot operate properly at these locations and will deprive UWB terminals of the opportunity to communicate even if the cellular terminal is not nearby.

The LDC can suppress interference to unknown primary system but limiting transmission time directly affects UWB performance.

Chapter 3

System model and the Integrated Terminal

In this chapter, we define the Integrated Terminal that can share the information between the cellular system and the UWB system, by mounting the modules of these two systems together. We also check what is possible by using the Integrated Terminal, that is, what kind of information can be shared, and what benefits can be achieved by sharing this information.

3.1 Coexistence scenario of UWB-WBAN and a cellular network

We consider a scenario where an UWB system based on IEEE 802.15.6 Wireless Body Area Network (BAN) [13] coexists with a cellular network.

A BAN consists of one or more nodes that act as sensors or actuators, and one coordinator to rule them all, forming a star topology. We assume that one user employs one BAN to monitor health information or vital signs such as heart rate, ECG, SpO_2 or body temperature, so a single BAN coordinator and several BAN nodes, i.e., UWB terminals are located within a few tens of centimeters. The information gathered through the BAN is delivered to the clinicians, nurses or other medical staffs via the external network, such as a cellular network, e.g. 4G, 5G and local 5G.

3.2 The Integrated Terminal

At first, as an example of the coexistence environment of the cellular system and the UWB system described in Chapter 2, we consider a system model, that consist of a cellular terminal used with BAN, another cellular terminal used alone without BAN, and a base station of a cell to which two cellular terminals belong. The system model is illustrated in Figure 3.1.

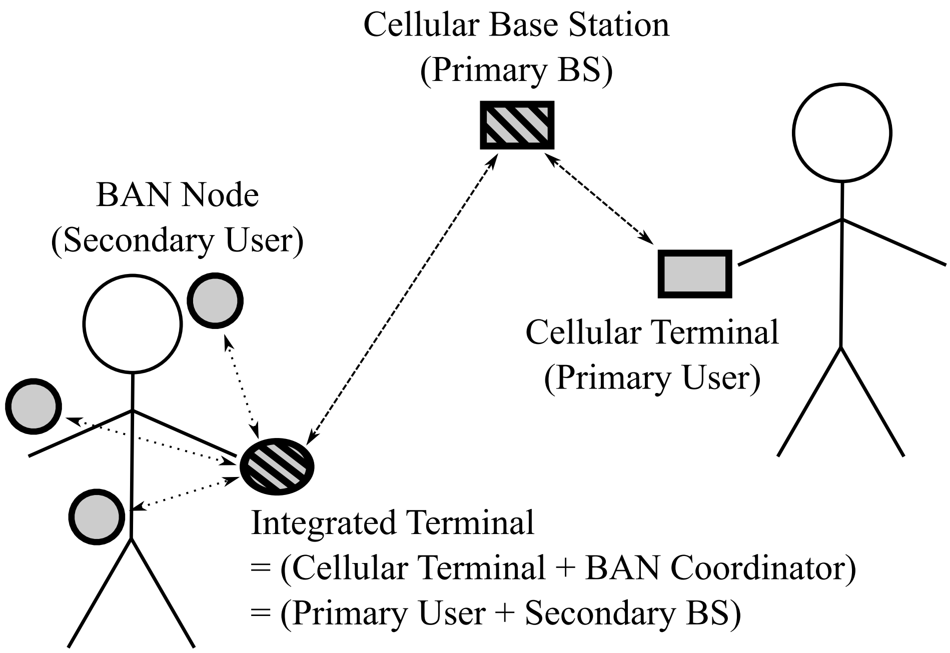

Figure 3.1 The system model with the Integrated Terminal

Let us investigate the flow of data in this system model. We assume that the BAN nodes are wireless interfaces attached to the medical sensors and deliver data such as heart rate and body temperature to the BAN coordinator. The path from this node to the coordinator is identified as an uplink. It should be noted that not all BAN nodes are sensors. Although the downlink is beyond the scope of the paper, it is also an important consideration in BAN nodes used for entertainment purposes, as well as insulin pumps that operate on data received from the coordinator.

Since the data delivered by each BAN node are collected in the BAN coordinator, it is only logical that the BAN coordinator directly transmits the information to the outside of the BAN. In order to realize this, the BAN coordinator should be equipped with a cellular module and be able to communicate with the cellular base station (BS) as a cellular terminal. We name such a terminal equipped with both a cellular terminal function and a BAN coordinator function an Integrated Terminal. An IT can join a cellular network as a cellular terminal, and control a BAN, i.e, an UWB network as a BAN coordinator at the same time.

In practical situation, a cellular terminal can be commercialized with an UWB module, just as a smartphone with Bluetooth. Although its role is limited to distance measurement and positioning, the UWB module is built into the iPhone 11 and iPhone 11 Pro. This shows that the realization of the Integrated Terminal is getting closer.

In a typical cellular network, there will also be ordinary terminals that are not Integrated Terminals. Cellular network terminals, including the Integrated Terminal, communicate with other terminals in the cell or outside, via a cellular base station (BS).

3.3 Formulation of system model

To begin with, we formulate the system model illustrated in Figure3.1. The number of cellular terminals is M, and that of UWB terminals is N. Note that M is a number including the Integrated Terminal. We denote the downlink transmit power of the BS for the ith cellular terminal as P_i^{pri}, and the channel gain from BS to ith cellular terminal as α_i^{pri}. Meanwhile, the uplink transmit power of the jth UWB terminal and the channel gain to the BAN coordinator are denoted by P_j^{sec} and α_j^{sec}, respectively. In addition, we denote the channel gain between the ith cellular terminal and the jth UWB terminal as $\alpha_{i,j}^{\mathrm{cross}}$. Note that the values of α are positive and have values in the range (0, 1]. ν_i^{pri} denotes the noise of the ith primary terminal.

For the sake of simplicity, we assume that only one UWB terminal transmits power at a particular point in time. Since the BAN uses time division multiple access (TDMA) as a subset of hybrid MAC protocol between contention base such as CSMA-CA and contention free such as TDMA, this represents an ideal case where no packet collisions occur. Then, the SINR experienced by the ith cellular terminal when the jth UWB terminal transmits its signal is given by the following equation:

$$\gamma_i^{\mathrm{pri}} = \frac{P_i^{\mathrm{pri}}\,\alpha_i^{\mathrm{pri}}}{P_j^{\mathrm{sec}}\,\alpha_{i,j}^{\mathrm{cross}} + \nu_i^{\mathrm{pri}}}, \tag{3–1}$$

where $1 \leq i \leq M$ and $1 \leq j \leq N$.

Let $\gamma_{\mathrm{th}}^{\mathrm{pri}}$ be the SINR required for the cellular terminal to communicate. Then, the inequality that the transmission power control (TPC) algorithm must satisfy is as follows:

$$\gamma_i^{\mathrm{pri}} \geq \gamma_{\mathrm{th}}^{\mathrm{pri}}. \tag{3–2}$$

Rewriting this inequality (3–2) using (3–1) yields the following inequality,

$$P_j^{\mathrm{sec}} \leq \frac{1}{\alpha_{i,j}^{\mathrm{cross}}}\left(\frac{P_i^{\mathrm{pri}}\,\alpha_i^{\mathrm{pri}}}{\gamma_{\mathrm{th}}^{\mathrm{pri}}} - \nu_i^{\mathrm{pri}}\right). \tag{3–3}$$

As a result, the maximum permissible transmit power for the jth UWB terminal P_j^{sec} is derived.

3.4 Parameters shared by the Integrated Terminal

Most of the parameters appearing in (3–3) are those of the cellular network, which are unknown to the jth UWB terminal that needs determine its transmit power P_j^{sec}. We propose an algorithm which the UWB network obtains and estimates these parameters through the cellular module on the Integrated Terminal and exploits them to determine the transmit power of the UWB terminal. The proposed algorithm uses the cellular module of Integrated Terminal, instead of the limited hardware of the UWB nodes. Therefore, it is possible to accurately acquire the parameters of the cellular network, thereby precisely controlling the transmit power of the UWB terminal so as not to interfere with the cellular network.

3.4.1 The channel gain between the cellular terminal and the UWB terminal

In a typical wireless network, a channel between a transmitter and a receiver is estimated by transmitting and receiving a pre-known reference signal, or a preamble. However, since the cellular network and the UWB network are different systems, it is impossible to use a preamble to estimate a channel between terminals of each network.

In the Integrated Terminal in which the UWB module and the cellular module are mounted on the same device, it can be considered that the signal power received by the UWB module is the interference power received by the cellular module.

A terminal equipped with only a cellular module, not an integrated terminal, also participates in a cellular network. In this case, the cellular-only terminal reports the received interference power to the Integrated Terminal through the cellular network. The Integrated Terminal estimates the channel using the interference power received by the cellular-only terminal and the transmission power of the UWB terminal transmitted at that time.

3.4.2 Parameters required to determine the permissible interference power of the cellular terminal

In order to determine the permissible interference power of the cellular terminal, the receiving power of desired signal and the desired SINR of the cellular terminal are required. The received power of the desired signal for the cellular terminal is represented as the product of the transmission power of the base station P_i^{pri} and the channel gain to the base station α_i^{pri}. Since this value is dynamically controlled by the cellular system to avoid inter-user interference, it is difficult for the UWB system to detect it. However, if the Integrated Terminal participates in the cellular network, the cellular terminal may notify the Integrated Terminal of its received power of desired signal through the cellular network and share this value with the UWB network. The desired SINR of the cellular terminal can also be shared in the UWB network in the same way.

3.5 Level of integration

The point of the Integrated Terminal is to share the information of the cellular network with the UWB network using the Integrated Terminal. Depending on how detailed and how fast the parameters of the cellular network can be shared, various scenarios can be considered. To classify these scenarios, we propose to use the concept of Integration Level.

3.5.1 Integration Level 0

The case where two separate modules are mounted in one terminal is defined as the Integration Level 0. At this level, the two modules do not exchange information with each other and perform their communication independently. In the case of smartphones currently on the market, modules of secondary systems such as UWB, Wi-Fi, and Bluetooth are installed along with modules of the cellular network, which are the primary systems. However, since these modules do not work in conjunction with each other yet, this case corresponds to integration level 0. Most terminals currently on the market remain at this level, and it is hard to use the term Integrated Terminal to refer to these terminals.

3.5.2 Integration Level 1

The case where two modules are mounted in one terminal and one module can acquire some of the parameters from the other module at certain intervals is defined as the Integration Level 1. An example of realizing this level is that when a cellular module receives a beacon, it records its information such as receiving power in a shared memory, and the UWB module gets its value from the shared memory whenever required. In this case, the frequency at which the UWB module can acquire information from the cellular network is determined by the beacon interval of the cellular network.

3.5.3 Integration Level 2

The case where one module can acquire parameters from another module in real time is defined as the Integration Level 2. This level assumes the ideal situation where the primary and secondary systems can be managed by one MAC protocol. Since the UWB module can acquire information such as the reception signal of the cellular module in real time, more precise control is possible, but the complexity of the module increases.

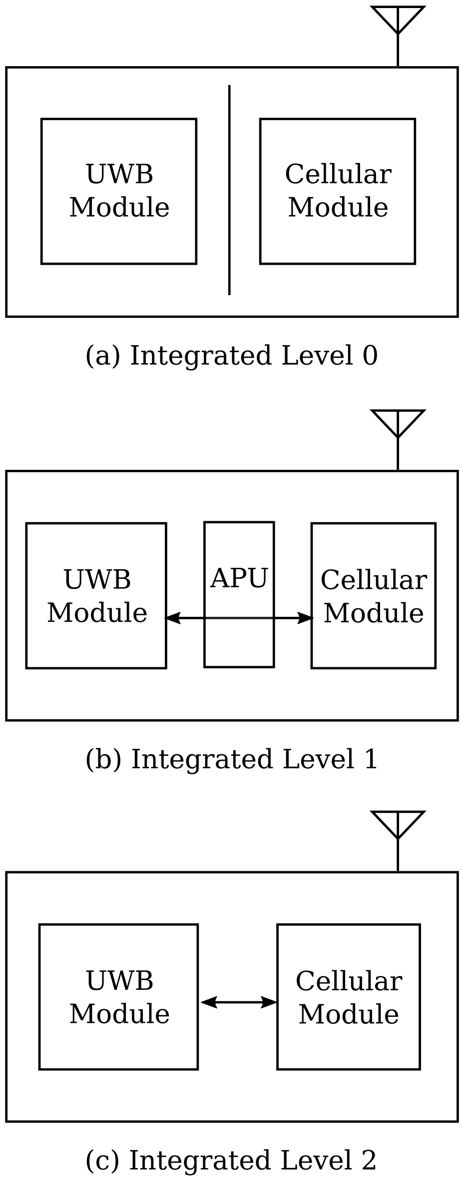

Figure 3.2 Various Integrated Levels

This paper mainly deals with the Integration Level 1, which can be realized by minor modification of the current system. The Integration Level 2 is also investigated to show how much performance improvement can be achieved by the Integration Level 2.

Chapter 4

Transmission power control

In the previous chapter, we have seen that what information can be shared from the cellular network to the UWB network using the Integrated Terminal. In this chapter, we propose a novel method on how to control the transmission of UWB using new information obtained through the Integrated terminal. Specifically, a proposed algorithm that determines the transmission power of UWB terminals such as UWB-BAN nodes and coordinator so as not to interfere with the cellular terminals beyond the permissible level, by acquiring parameters such as channel state information of the cellular system via the Integrated Terminal, is described.

The operations of this algorithm can be grouped as follows; initialization, transmission, interference monitoring, and transmission power updating. A detailed sequence diagram of the proposed algorithm is shown in Figure 4.1.

4.1 Initialization

A BAN coordinator broadcasts beacons i.e, control signals for synchronization. The Integrated Terminal sends the control signal including an initial value of the transmit power P_j^{sec} for the UWB terminals in the network (Figure 4.1a), and each UWB terminal sets its own transmit power accordingly (Figure 4.1b). The initial value should be determined to a value that satisfies the existing regulations, such as spectrum mask.

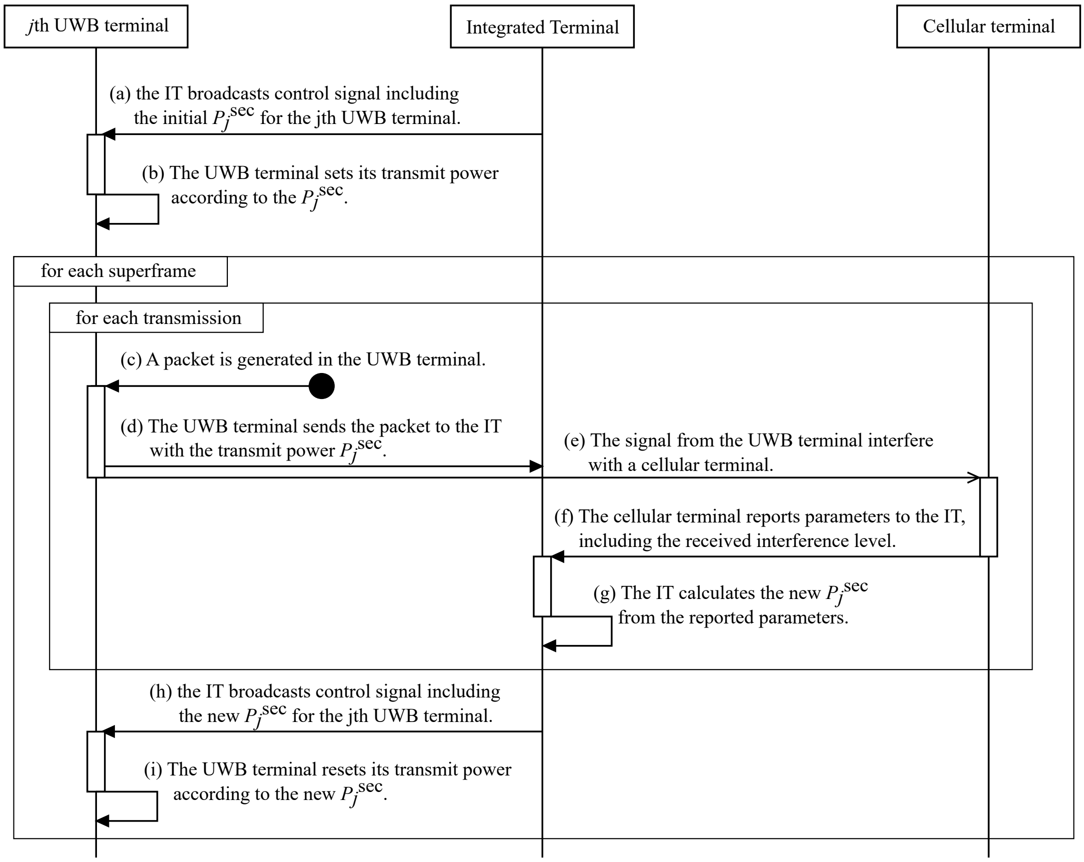

Figure 4.1 The sequence diagram of the proposed algorithm

4.2 Transmission

When a packet is generated in the UWB terminal (Figure 4.1c), the UWB terminal sends its packet to the Integrated Terminal, which is the BAN coordinator, at the transmission power determined in the previous step (Figure 4.1d). At this time, the signal from the UWB terminal appears as interference in the cellular terminal (Figure 4.1e).

4.3 Interference monitoring

Cellular terminals monitor the interference received from UWB terminals for a predetermined amount of time Δt, and deliver this value to the Integrated Terminal. Since cellular terminals already have a channel monitoring function for selecting a cell to which they belong or for running their own transmission power control algorithm, this can be done with minimal modification of the cellular system.

The received signal of the ith cellular terminal $y_i^{\mathrm{I}}(t)$ at time t, due to the interference from an UWB terminal can be expressed by the following equation:

$$y_i^{\mathrm{I}}(t) = \sum_{j=1}^{M} \sqrt{P_j^{\mathrm{sec}}\, \alpha_{i,j}^{\mathrm{cross}}}\, \delta_j^{\mathrm{sec}}(t)\, u_j^{\mathrm{sec}}(t) + n_i^{\mathrm{pri}}(t), \tag{4–1}$$

where $\delta_j^{\mathrm{sec}}(t)$ is a function indicating whether or not the jth UWB terminal transmits at time t, and has a value of 1 when it is transmitting, and 0 otherwise. $u_j^{\mathrm{sec}}(t)$ denotes a pulse shape used by the jth UWB terminal, and $n_i^{\mathrm{pri}}(t)$ denotes noise observed at the ith cellular terminal.

As explained in section 3.3, we assume that only one UWB terminal transmits its signal during Δt with an appropriate access control scheme (hence $\sum_j^M \delta_j^{\mathrm{sec}}(t) = 1$.) In addition, for the sake of simplicity, we assume that P_j^{sec}, $\alpha_{i,j}^{\mathrm{cross}}$, and $\delta_j^{\mathrm{sec}}(t)$ are constant over time Δt. Then, the energy of the received signal at the ith cellular terminal E_i^{I} can be expressed by the following equation:

$$\begin{aligned} E_i^{\mathrm{I}} &= \int_{\Delta t} \left\{ y_i^{\mathrm{I}}(t) \right\}^2 dt \\ &= P_j^{\mathrm{sec}}\, \alpha_{i,j}^{\mathrm{cross}} \int_{\Delta t} \left\{ u_j^{\mathrm{sec}}(t) \right\}^2 dt \\ &\quad + 2\sqrt{P_j^{\mathrm{sec}}\, \alpha_{i,j}^{\mathrm{cross}}} \int_{\Delta t} u_j^{\mathrm{sec}}(t)\, n_i^{\mathrm{pri}}(t)\, dt \\ &\quad + \int_{\Delta t} \left\{ n_i^{\mathrm{pri}}(t) \right\}^2 dt, \end{aligned} \tag{4–2}$$

where $j : \delta_j^{\mathrm{sec}} = 1$.

The integral of the first term in (4–2) represents the energy of the pulse used by the jth UWB terminal, and is a known value throughout the UWB system. To simplify the expression, we consider the average power of the pulse as a normalized value of 1. The integral of the second term in (4–2) can be regarded as zero, because the pulse and noise are uncorrelated. The integral of the third term in (4–2) represents the energy of the noise, and can be expressed as $\nu_i^{\mathrm{pri}} \Delta t$. Thus, the interference power received by the ith cellular terminal P_i^{I} can be expressed as follows:

$$\begin{aligned} P_i^{\mathrm{I}} &= E_i^{\mathrm{I}} / \Delta t \\ &= P_j^{\mathrm{sec}}\, \alpha_{i,j}^{\mathrm{cross}} + \nu_i^{\mathrm{pri}}, \end{aligned} \tag{4–3}$$

where $j : \delta_j^{\mathrm{sec}} = 1$.

The ith cellular terminal reports P_i^{I} to the Integrated Terminal as its received interference level from the UWB terminal (Figure 4.1f), along with the signal level of the desired signal from the cellular BS P_i^{S} $(= P_i^{\mathrm{pri}} \cdot \alpha_i^{\mathrm{pri}})$ and the desired SINR $\gamma_{\mathrm{th}}^{\mathrm{pri}}$. Various communication techniques can be considered for a cellular terminal to share these parameters with an Integrated Terminal. For example, a cellular terminal may pass parameters directly to an Integrated Terminal using device-to-device (D2D) communication. Alternatively, since cellular terminals report their channel status information (CSI) such as interference level to a cellular BS, the cellular BS may include this information in a control signal and broadcast it to the Integrated Terminal.

4.4 Transmission power updating

Since the Integrated Terminal acquires the value of the received interference power at the ith cellular terminal P_i^{I}, and knows δ_j^{sec} that indicating which UWB terminal has transmitted at the observation time, and thus it can calculate the channel gain between the ith cellular terminal and the jth UWB terminal $\alpha_{i,j}^{\mathrm{cross}}$ as follows:

$$\alpha_{i,j}^{\mathrm{cross}} = \frac{P_i^{\mathrm{I}} - \nu_i^{\mathrm{pri}}}{P_j^{\mathrm{sec}}}, \tag{4–4}$$

where $j : \delta_j^{\mathrm{sec}} = 1$.

Then, the new transmit power for the jth UWB terminal $\hat{P}_j^{\mathrm{sec}}$ is calculated from (3–3) as follows (Figure 4.1g):

$$\hat{P}_j^{\mathrm{sec}} \leq \frac{P_j^{\mathrm{sec}}}{P_i^{\mathrm{I}} - \nu_i^{\mathrm{pri}}} \left(\frac{P_i^{\mathrm{pri}} \, \alpha_i^{\mathrm{pri}}}{\gamma_{\mathrm{th}}^{\mathrm{pri}}} - \nu_i^{\mathrm{pri}} \right), \tag{4–5}$$

where $j : \delta_j^{\mathrm{sec}} = 1$.

Finally, the Integrated Terminal broadcasts a control signal containing the new transmit power $\hat{P}_j^{\mathrm{sec}}$ (Figure 4.1h). The UWB terminal also resets its transmit power accordingly (Figure 4.1i).

Chapter 5

Performance evaluation of the transmission power control

In order to evaluate the performance of the proposed algorithm in a straightforward way, and to focus on the coexistence scenario considered in this paper, the simulation specification is set as follows. The simulation specifications are summarized in Table 5.1.

Table 5.1 Summary of simulation specifications

Parameters	Values
center frequency	3.4 GHz
permissible interference level of cellular terminal	-114.8 dBm/MHz
channel environment	free space propagation

- A frequency band of 3.4 GHz, which has the highest allowable effective isotropic radiated power (EIRP) specified in the FCC's spectral mask, is adopted. This band is also used in LTE and 5G.
- It is intuitive to determine that the cellular terminal is disturbed when the SINR at the cellular terminal does not reach the desired SINR. However, parameters such as the transmission power of the cellular BS P_i^{pri}, the channel gain between the cellular BS and the cellular terminal α_i^{pri}, and the desired SINR at the cellular terminal $\gamma_{\mathrm{th}}^{\mathrm{pri}}$ are exceedingly dynamic and vary depending on the layout of terminals, as well as the specifications of the cellular system such as modulation scheme. Therefore, in order to evaluate the proposed algorithm without depending on the specific

implementation method of the cellular system, the criterion of whether the cellular terminal is disturbed is based on whether the power density of the interference signal is higher than -114.8 dBm/MHz [14].

- Although the fading model represents a more realistic situation, the distance between terminals is the most influential factor for BAN which uses UWB signals with high attenuation at low power in close range. Therefore, in order to confirm the performance according to the distance between terminals, the free space propagation model is used.

5.1 Interference to cellular networks

The maximum permissible transmission power for an UWB terminal placed at given distances from the victim cellular terminal is shown in Figure 5.1. The maximum permissible transmit power is defined as a transmit power of the UWB terminal, whose interference power at the victim cellular terminal is below the permissible interference level. Since the regulations are defined in terms of effective isotropic radiated power (EIRP), the transmission powers are calculated in EIRP.

Figure 5.1 explains that as the distance to the cellular terminal is closer, the power UWB terminal can transmit without interfering to the cellular terminal beyond the permissible level becomes smaller. Especially, it is noteworthy that when the cellular terminal is closer than 1.2 m, the permissible level is lower than -70 dBm/MHz. This means that even with a transmission power of -70 dBm/MHz, the transmission power allowed for an UWB terminal not using DAA, interference cannot be sufficiently avoided.

Figure 5.2 shows the interference level received by the victim cellular terminal when using the integrated terminal to control the transmit power of the UWB terminal and when using the conventional DAA scheme.

From Figure 5.2, we can see that the proposed algorithm (solid line) maintains the interference level received by the cellular terminal at -114.8 dBm/MHz, which is a permissible level for the cellular network. On the other hand, in

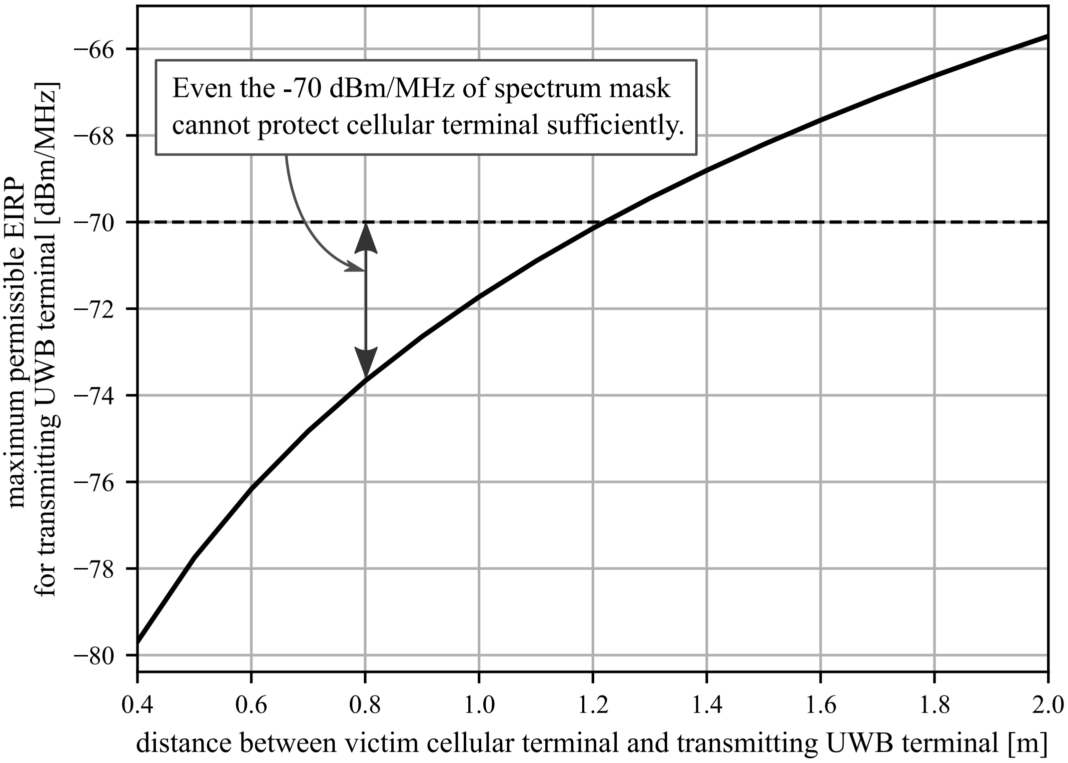

Figure 5.1 Maximum permissible transmission power for an UWB terminal

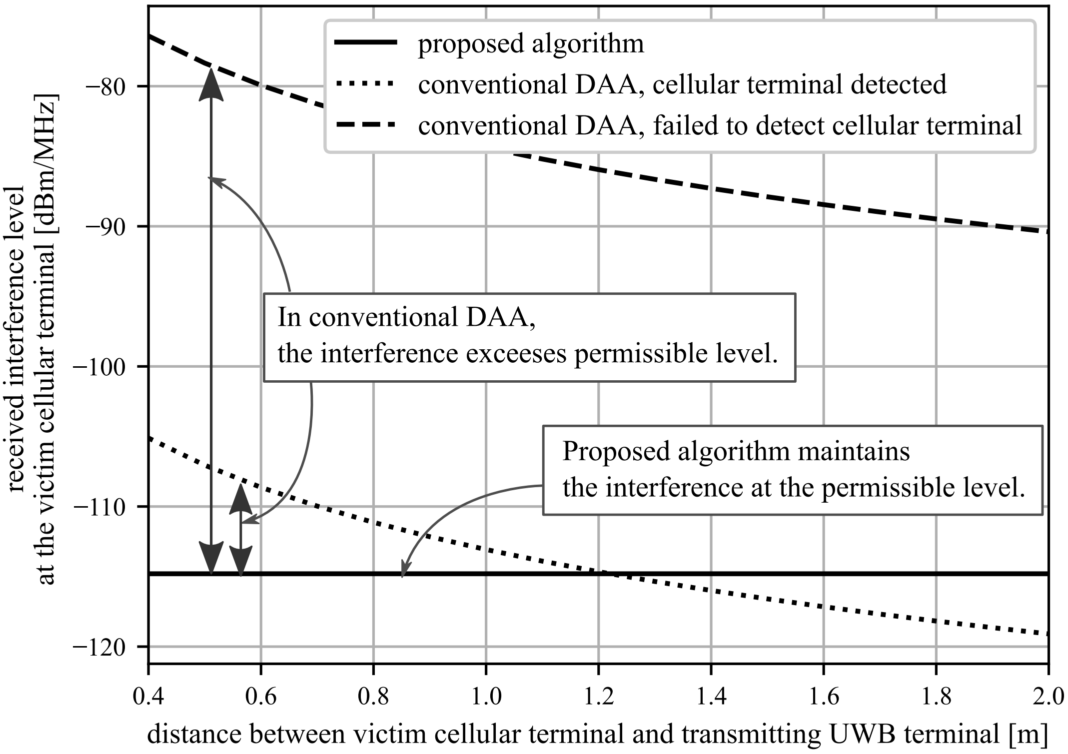

Figure 5.2 Interference level at the victim cellular terminal

the conventional DAA scheme, when the detection of the cellular terminal fails (dashed line), the UWB terminal transmits at -41.3 dBm/MHz, which is the maximum transmission power of the current regulation. If there is a cellular terminal within a given distance (up to 2 m in this simulation), the result is that the interference is always exceeded the permissible level. Even if the detection of the cellular terminal is successful and the UWB terminal transmits its signal at a transmission power of -70 dBm/MHz (dotted line), as anticipated in Figure 5.1, depending on the distance between the transmitting UWB terminal and the victim cellular terminal, the cellular terminal may experience excessive interference than the permissive level.

5.2 Performance of UWB system

The performance of the UWB system is evaluated in terms of the received power of the UWB signal at the integrated terminal, which is a BAN coordinator. Typically the performance of an UWB system is expressed in terms of the offered load and its throughput, but since these values are directly tied to the received power level of the UWB signal, it is more intuitive to evaluate the performance of the transmit power control algorithm with the received power level.

A minimum set of the Integrated Terminal (IT), the transmitting UWB terminal (SU), and the victim cellular terminal (PU) is used for the simulation. As the distance between the victim cellular terminal and the transmitting UWB terminal, two values of 0.6 m and 1.8 m are selected. The distance of 0.6 m represents a case that the cellular terminal and the UWB system are used by the same user, thus the victim cellular terminal and the transmitting UWB terminal are located close to each other. In contrast, a distance of 1.8 m represents a case that the UWB system affects the cellular terminal of another person. Figure 5.3 describes the layout of the terminals used in this simulation.

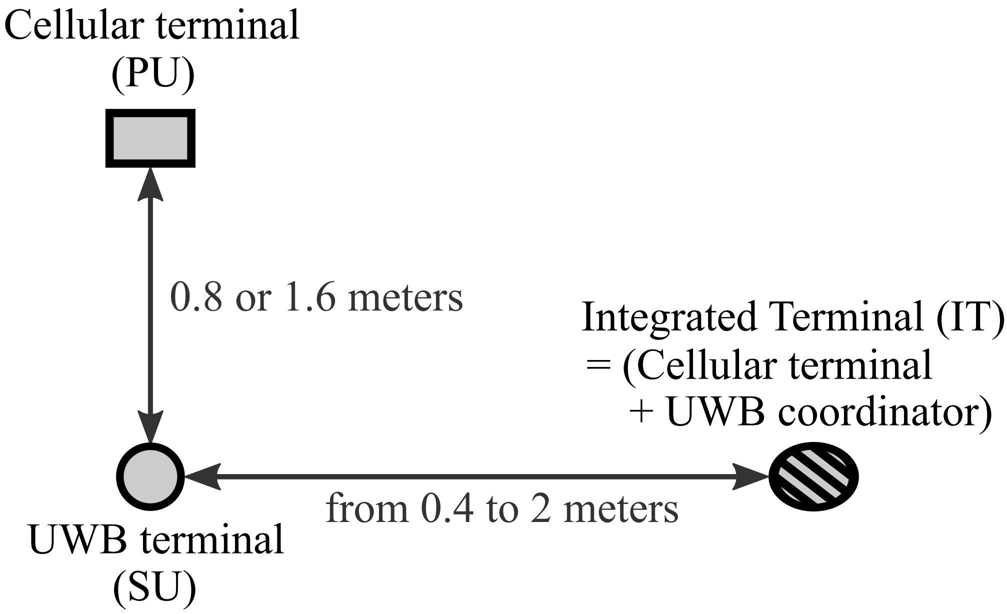

Figure 5.3 Layout of the terminals

5.2.1 Integration Level 1

Received signal level of UWB signal at the UWB module in the IT is shown in Figure 5.4 and Figure 5.5. The result of the conventional DAA scheme which failed to detect cellular terminal is omitted, because its interference level at the victim cellular terminal extremely excesses the permissible level.

Figure 5.4 shows a case where the distance between the victim cellular terminal and the transmitting UWB terminal is 0.8 m. In the range of 0.4 m to 0.8 m on the horizontal axis, the IT is closer than the victim cellular terminal from the transmitting UWB terminal. Therefore, the proposed algorithm operates so that the interference power at the cellular module in the IT does not exceed the permissible level. As a result, in this range, the desired UWB signal level at the UWB module of the IT is maintained at the permissible level of the interference power. On the other hand, in the range of 0.8 m to 2.0 m, the victim cellular terminal is closer than the IT from the transmitting UWB terminal. Therefore, the proposed algorithm operates so that the interference power at the victim cellular terminal does not exceed the permissible level. As a result, the performance of the UWB network is degraded, in order to avoid introducing interference

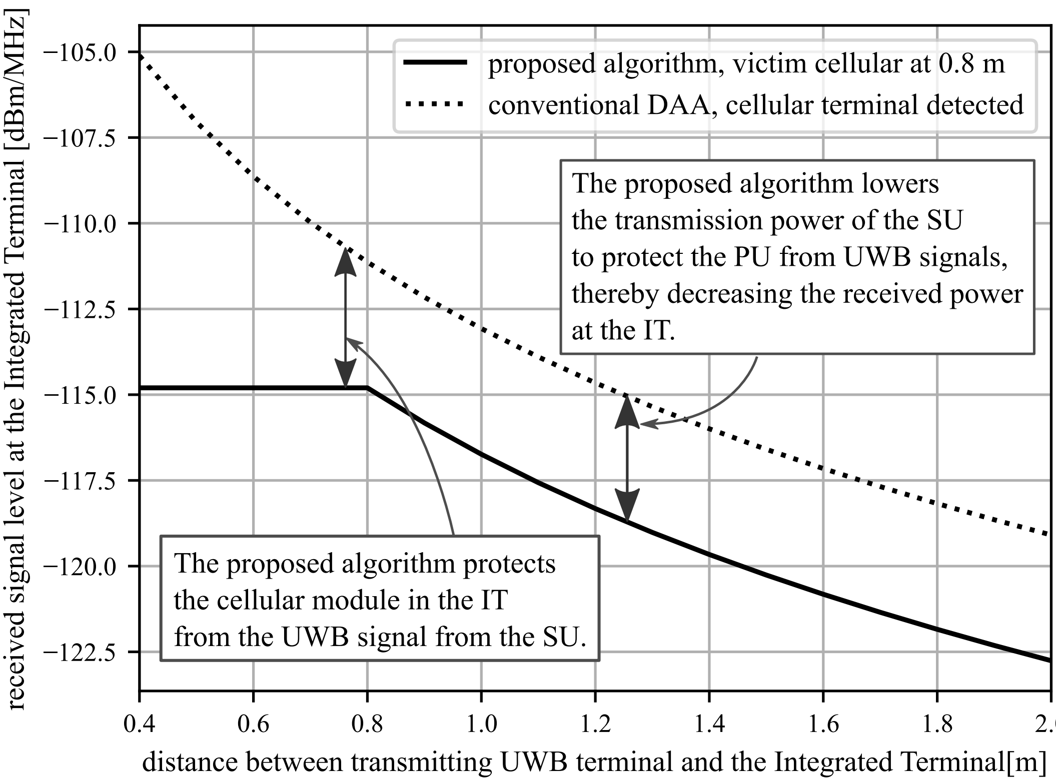

Figure 5.4 Received signal level at the Integrated Terminal, in which distance between victim cellular terminal and transmitting UWB terminal is 0.8 m

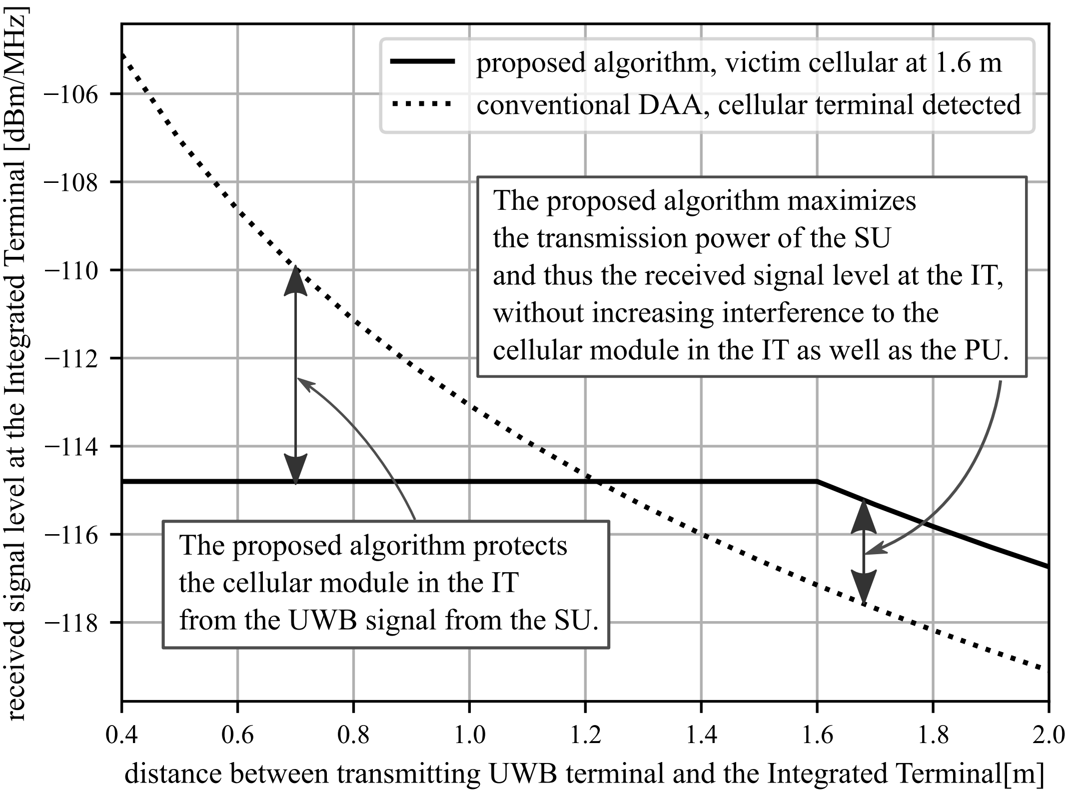

Figure 5.5 Received signal level at the Integrated Terminal, in which distance between victim cellular terminal and transmitting UWB terminal is 1.6 m

beyond the permissible level to the cellular network, which is a top priority for the proposed algorithm.

Figure 5.5 shows a case where the distance between the victim cellular terminal and the transmitting UWB terminal is 1.6 m. Similarly to Figure 5.4, in the range where the transmitting UWB terminal and the IT are close, the proposed algorithm operates so that the interference power in the cellular module in the IT does not exceed the permissible level. However, since the proposed algorithm maximizes the transmission power of the UWB terminal under the constraint of the interference power, it can increase the received level of the desired signal at the IT, in a range where a signal transmitted by an UWB terminal with power of -70 dBm/MHz using the conventional DAA method is attenuated below the permissible interference level.

5.2.2 Integration Level 2

The Integration Level 2 assumes a case in which the Integrated Terminal can separate the UWB signal and the cellular signal. This result is shown in Figure 5.6.

In this case, since the Integrated Terminal does not need to consider the interference to the cellular module mounted on it, it controls the UWB terminal transmit power so that only the interference to the victim cellular terminal is below the permissible level.

Since the level of the UWB signal received by the Integrated Terminal depends only on the distance from the victim cellular terminal, it can be seen that if the distance between the UWB terminal and the Integrated Terminal is closer than that of the victim cellular terminal, the Integration Level 2 can achieve a higher receiving power than that of the Integration Level 1.

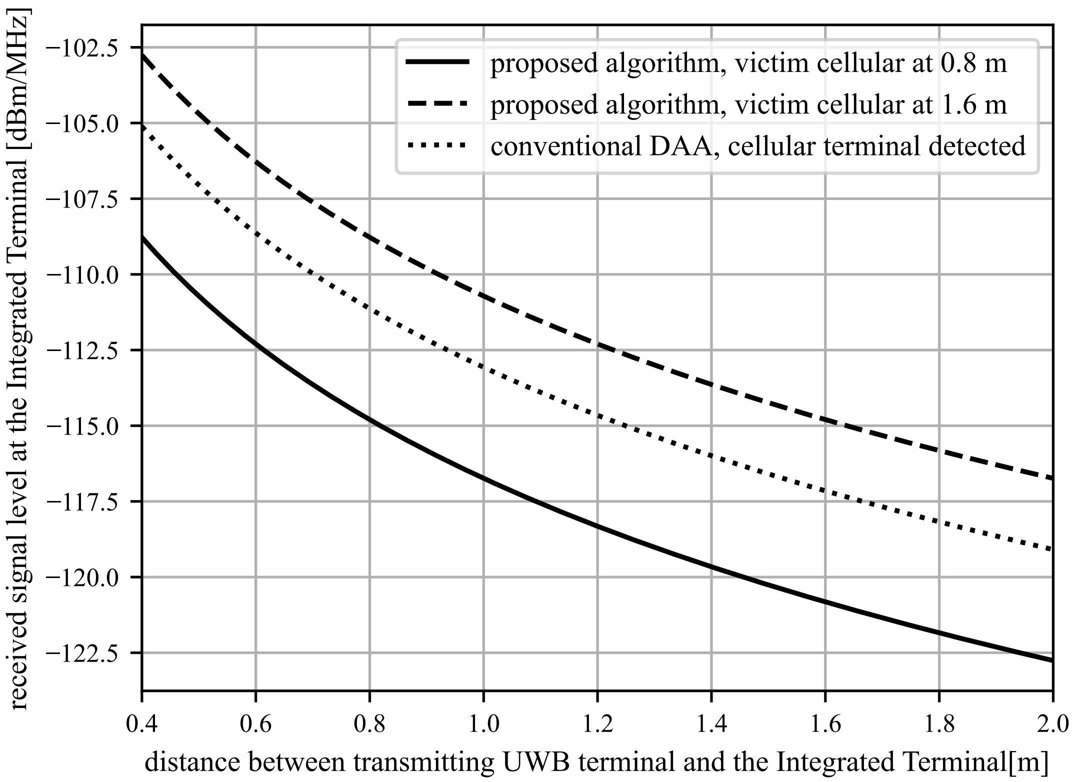

Figure 5.6 Received signal level at the Integrated Terminal, Integration Level 2, in which distance between victim cellular terminal and transmitting UWB terminal is 0.8 m and 1.6 m

Chapter 6

Spreading sequence length control

In this Chapter, a new scheme of transmission control using variable length of spreading sequence of IR-UWB is proposed and described in order to improve performance of the proposed transmission power control in Chapter 4.

Some performance analysis in Chapter 5 confirms that the proposed transmission power control scheme can improve performance of secondary UWB ad-hod network such as throughput while maintaining permissible interference to primary cellular network. However, in case of below 1.2m separate distance between nodes of primary cellular and secondary UWB networks, permissible emission power or transmission power from UWB node may be below -100 dBm/MHz, which is close to noise level. So, in case of low SNR for UWB node, it seems infeasible to ensure performance of UWB network.

In order to solve this problem to get better SNR for UWB network, a new scheme of control using variable length of spreading sequence of IR-UWB. Using direct sequence (DS) in IR-UWB, correlation detection can increase accumulated UWB signal power in proportion to the length of spreading sequence, i.e. processing gain [15]. However, frequency bandwidth of UWB network cannot spread more than normal IR-UWB. It means that time duration of pulse cannot be shortened unlike typical DS spread spectrum or UWB to keep the same data rate. For instance, when n pulses corresponding to n chips length of M-sequence is used to transmit 1 bit datum, time duration of the pulse may be shorten to $1/n$ or its frequency bandwidth be n times wider spread while keeping the same data rate. Therefore, in this proposal, time duration of pulses is not shortened, then the bandwidth is the same while data rate decreases to $1/n$.

If we look at major applications of UWB in radar and remote keyless system of an automobile, data rate is not important but ranging accuracy is keen. So, this proposed transmission control of spreading sequence length may be useful.

6.1 Bit error rate for single pulse

The bit error rate for the single pulse is shown in Figure 6.1. The Integration Level 1 is assumed for the proposed algorithm in this figure.

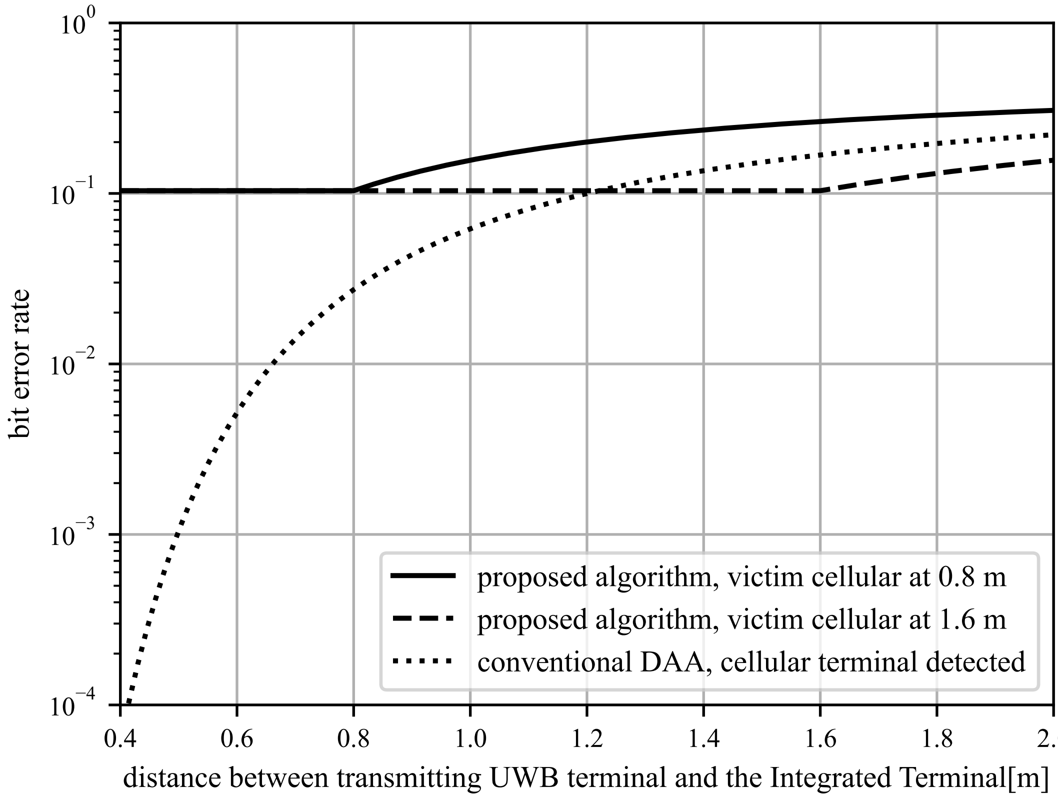

Figure 6.1 Bit error rate at the Integrated Terminal with Integrated Level 1

Compared with the conventional method, the bit error rate is high even when the UWB terminal and the integrated terminal are close. This result is mainly due to the fact that the proposed scheme has to protect the cellular module in the Integrated Terminal. In fact, the bit error rate of the conventional method of transmitting at -70 dBm/MHz is still high to ensure a reliable communication of UWB link.

Figure 6.2 shows that the bit error rate can be increased with applying the Integration Level 2.

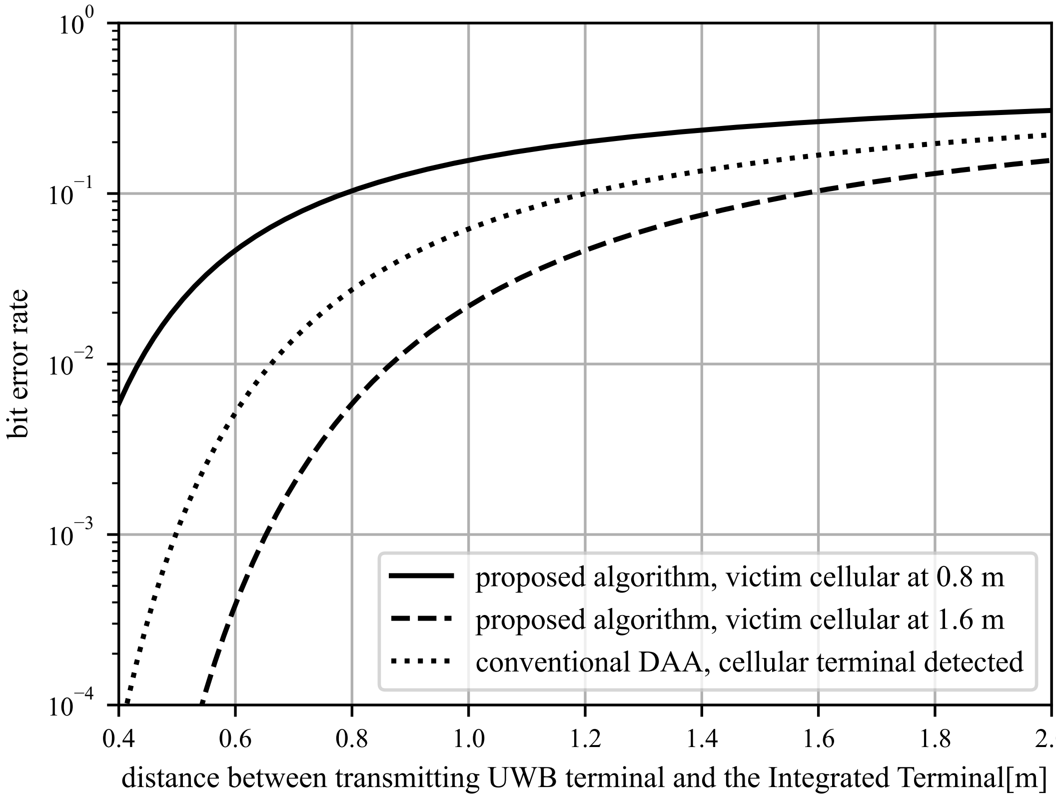

Figure 6.2 Bit error rate at the Integrated Terminal with Integrated Level 2

In the Integration Level 2, the UWB signal is separated from the cellular signal in the time domain. So, the cellular module mounted in the Integrated Terminal does not receive interference signal from the UWB node. Nevertheless, when the cellular terminal is located close to the UWB node, the proposed system further lowers the transmission power of the UWB node to protect the cellular terminal, resulting in high bit error rate. In case that the distance to the victim cellular terminal is 1.6m, the bit error rate is lowered because the primary terminal is far and the UWB node can exploit more power. But, it is still high to establish a reliable UWB link.

6.2 processing gain with spreading sequence

To ensure reliable communication between the UWB link while protecting the cellular network, we propose to control the sequence length of the UWB signal, according to the desired bit error rate. Exploiting process gain, the UWB system can achieve higher bit error rate to ensure reliable communication.

The required process gain to achieve the bit error rate of 10^{-4} is shown in Figure 6.3.

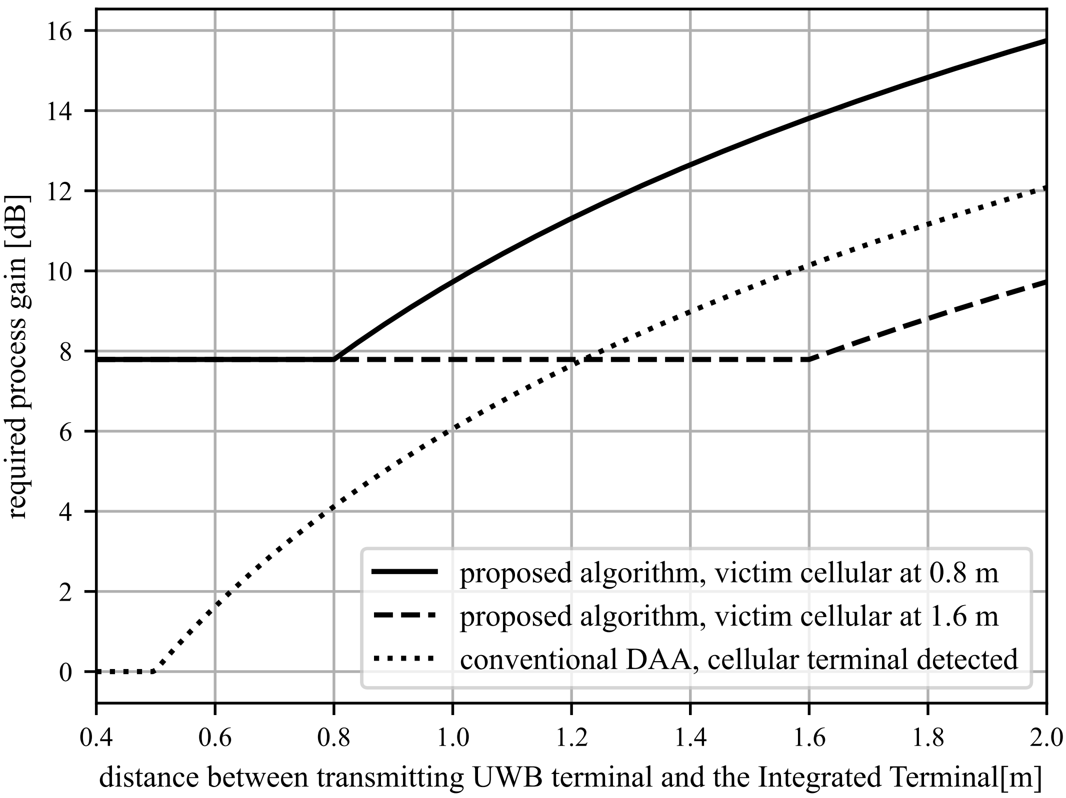

Figure 6.3 Required process gain to achieve BER of 10^{-4} with Integrated Level 1

The M-sequence is assumed to be used as a spreading sequence. The M-sequences has a length of $2^n - 1$, and the required sequence length is dependent to the required process gain. The required sequence length is shown in Figure 6.4 and Figure 6.5.

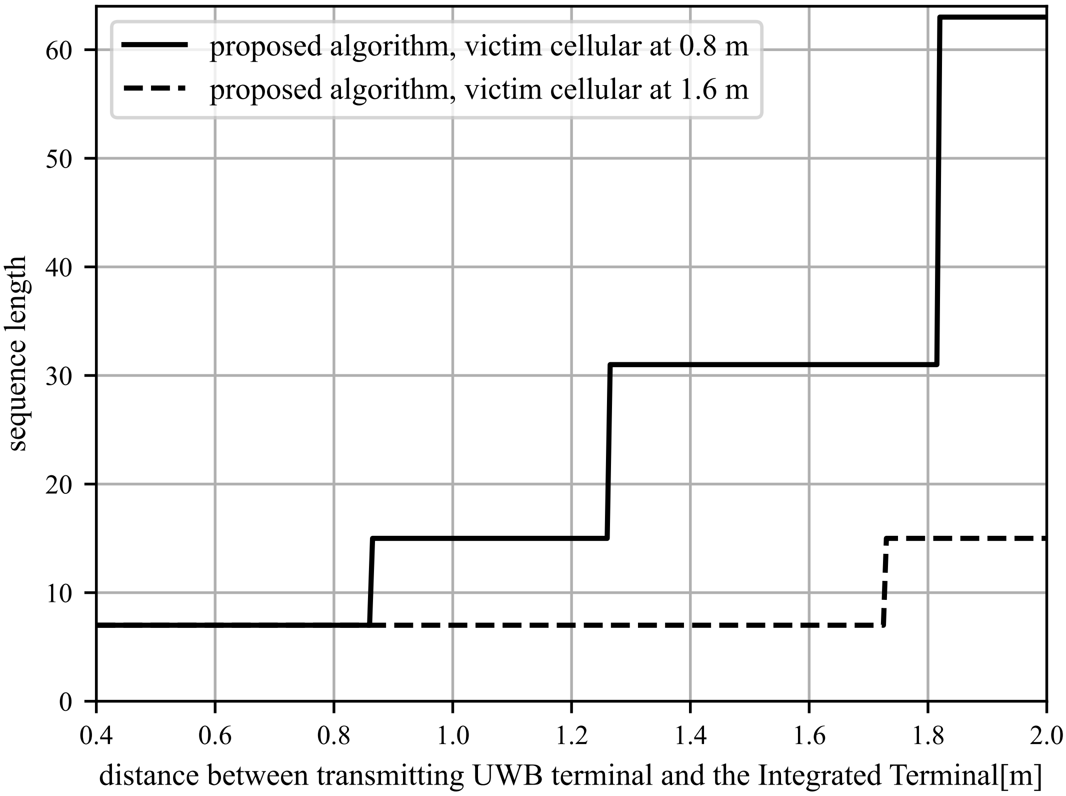

Figure 6.4 Sequence length to achieve BER of 10^{-4} with Integrated Level 1

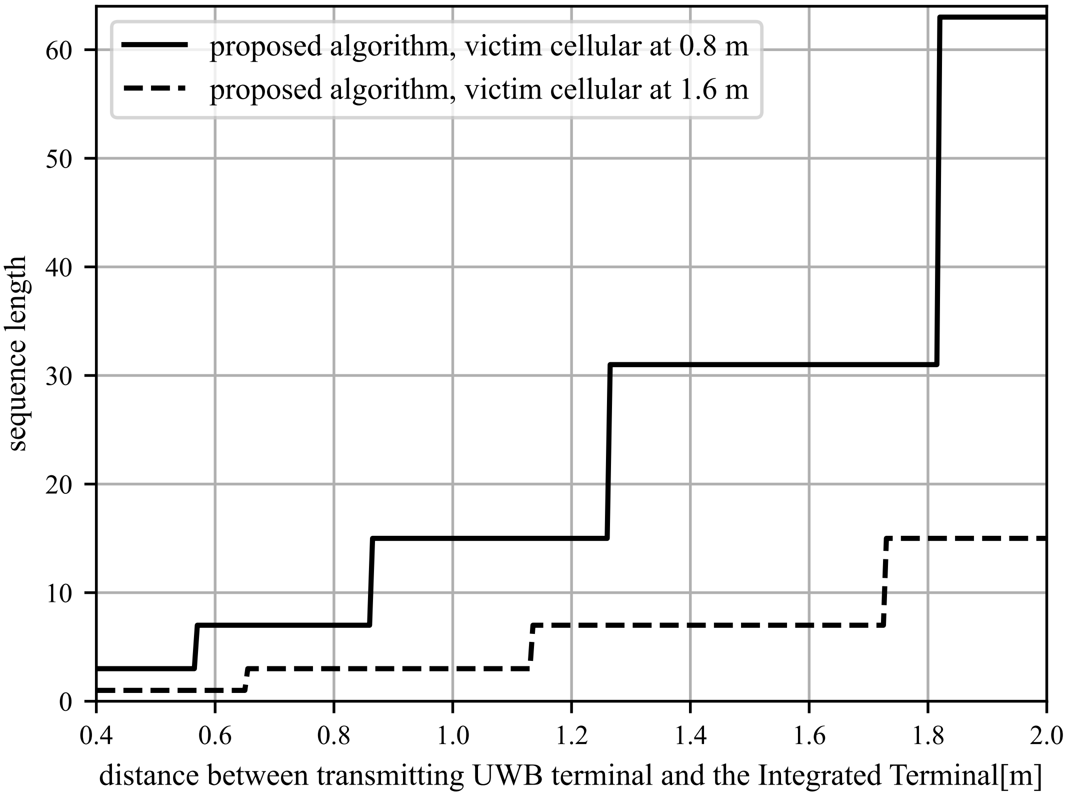

Figure 6.5 Sequence length to achieve BER of 10^{-4} with Integrated Level 2

6.3 Bitrate using spreading sequence

The Figure 6.6 and Figure 6.7 show the bitrate at the Integrated Terminal achieving bit error rate of 10^{-4}. Figure 6.6 is in case of the Integrated Level 1, and Figure 6.7 is of the Integrated Level 2.

As the distance to the UWB node increases, the path loss becomes severe. Therefore, to compensate for attenuation, the spreading sequence should be increased, and thus the bit rate decreases. Though, since the transmit power is dynamically controlled, we can see that the bitrate can be increased if the victim cellular terminal is in distance.

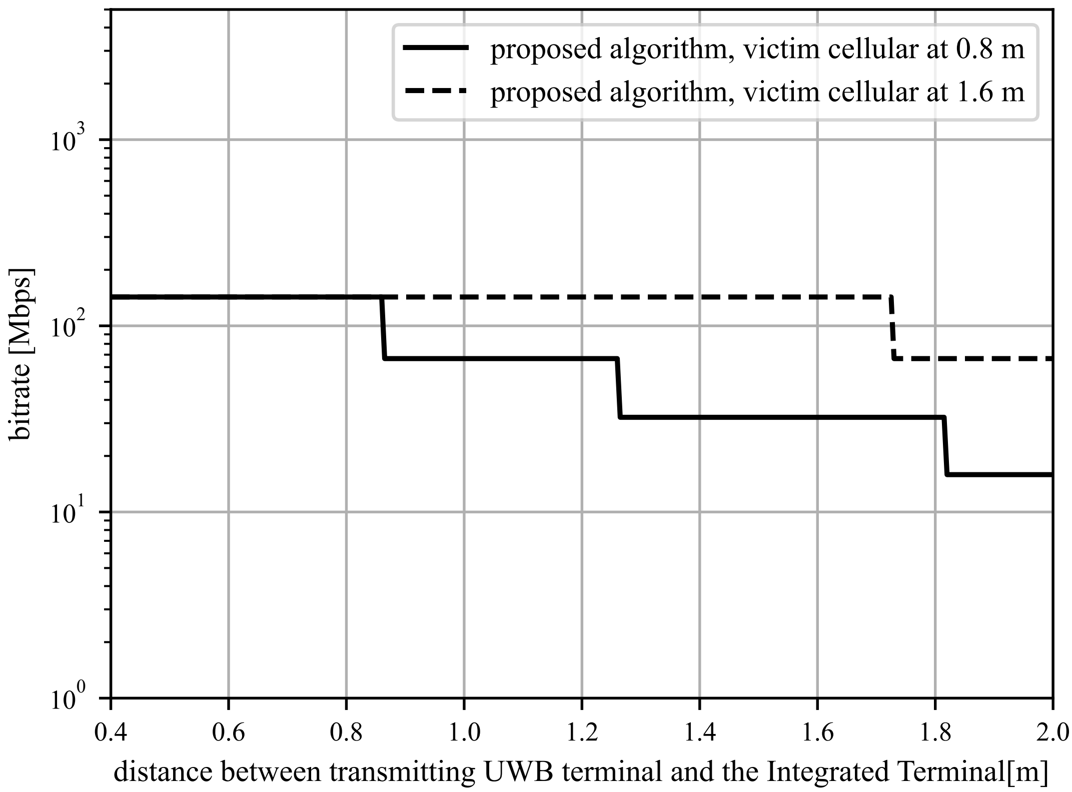

Figure 6.6 Bitrate at the Integrated Terminal achieving BER of 10^{-4} with Integrated Level 1

The advantages of the Integrated Level 2 can be confirmed with Figure 6.6. Even when the victim terminal is nearby, the bitrate can be increased by almost twice by using the Integration Level 2. Moreover, considering typical use cases of WBAN, it is rare for a user to use more than one cellular terminal. Assuming that the cellular terminal used by the user is only an Integrated Terminal, the bitrate can be increased further.

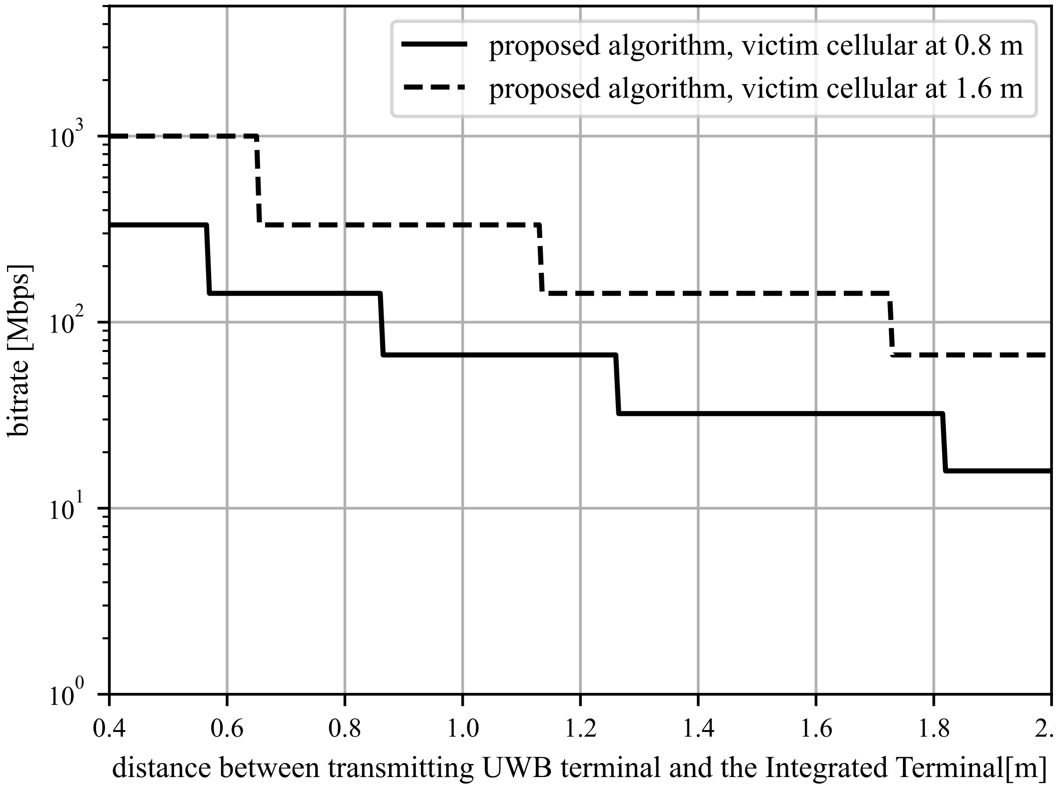

Figure 6.7 Bitrate at the Integrated Terminal achieving BER of 10^{-4} with Integrated Level 2

Depending on the type of UWB node, there are various QoS requirements. The Figure 6.6 and Figure 6.7 show the bitrate at the Integrated Terminal achieving bit error rate of 10^{-6}, for the higher QoS requirements.

It can be seen that as the bit error rate requirements become more stringent; the bit rate decreases.

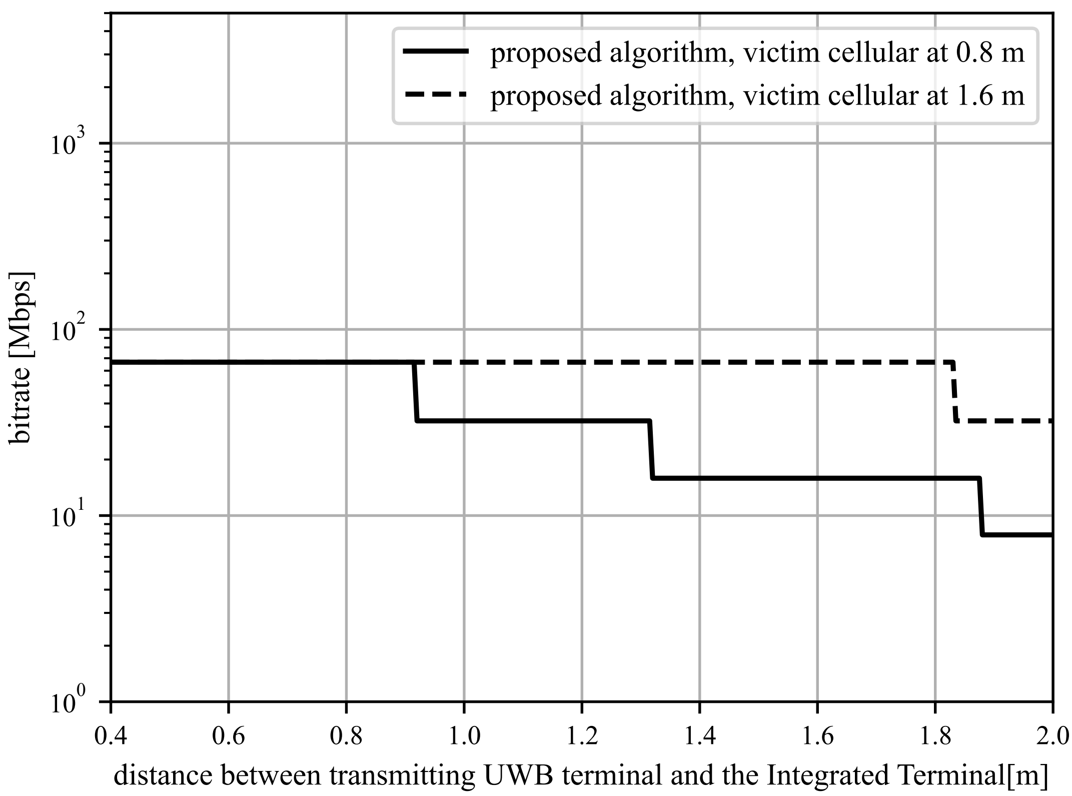

Figure 6.8 Bitrate at the Integrated Terminal achieving BER of 10^{-6} with Integrated Level 1

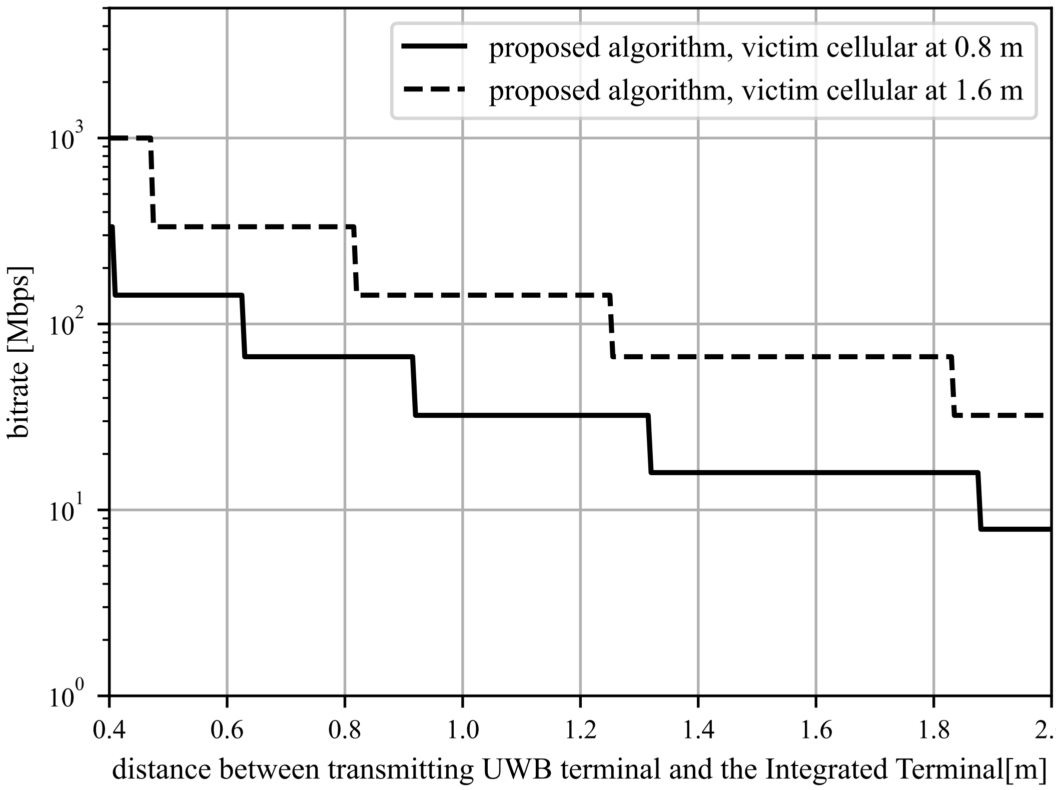

Figure 6.9 Bitrate at the Integrated Terminal achieving BER of 10^{-6} with Integrated Level 2

Chapter 7

Conclusion and future works

7.1 Conclusion

An algorithm that shares the parameters of the cellular system with the UWB system via the Integrated Terminal and determines the transmission power of the UWB terminals using these parameters, is presented. It has been shown that we can control the interference due to the signal of the UWB terminals received by the cellular terminal not to exceed the permissible level, by dynamically determining the upper limit of the transmission power of the UWB terminals according to the situation of the cellular system, instead of setting the predetermined constant. In addition, it has been shown that there is a case where the transmission power of UWB terminals can be increased, that is, the performance of the UWB system can be improved, while maintaining the interference on cellular terminals below the permissible level.

In addition, it was shown that by controlling the sequence length to cope with the severe transmit power constraints imposed on the UWB system, tens to hundreds Mbps of bitrates can be achieved in a short distance.

Numerical simulations are performed using a minimal set consisting of one cellular terminal, one Integrated Terminal combined with a cellular and a BAN coordinator module, and one UWB terminal as a BAN node, however, since the algorithm is designed to be scalable, it can be used even when there are more than one cellular or UWB terminal.

The relationship between the transmission power of the UWB terminal and the interference on the cellular terminal was also revealed through this study.

Concurrent regulations are insufficient to protect the communication of cellular terminals closer than about 1.2 m, but the proposed algorithm can protect the communication of cellular terminals in a very short distance also.

There are people who use smartphones and tablet computers at the same time already, and IoT will become more usual in the future, so it will be more casual for one person to use multiple cellular terminals within a range of 1 m. The results of this study can be used to determine the more practical value of the safety factor, or margin, applied to the transmission power regulation of UWB systems, and to amend the regulation to be more efficient. This is a timely issue as UWB modules will soon be installed in commercial smartphones such as iPhone 11 and 11 Pro as well as Android smartphones.

7.2 Future works

This paper has shown the upper limit of the bitrate, which is about PHY, assuming that the optimal MAC protocol is used. Simulation results of transmission power rather than throughput. The throughput considering access control with other terminals can more realistically evaluate performance in actual use situations. In detail, applying a specific packet format such as IEEE 802.16.5 WBAN to this algorithm can calculate the throughput for offered load, which is our future work.

If the estimation error of the interference level received by the cellular terminal increases, the interference on the cellular terminal may also exceed the permissible level, or the performance of the UWB system may deteriorate. Therefore, in order to make the proposed algorithm more reliable, the relationship between the accuracy of estimation error and the sensitivity of performance should be investigated.

In addition, we would like to mention the possible drawbacks of this proposed method. Since the additional process for estimation and sharing of the interference level received by the cellular terminal will increase computational complexity and power consumption, it is also required to evaluate this overhead. It is another future work to include the overhead in the algorithm to increase the effectiveness and the reliability of the proposed method.

Annex A

Update of UWB Radio Regulation in Japan [8]

Japanese radio regulation authority MIC (Ministry of Internal Affairs and Communications) has investigated technical requirement for ultra wide band (UWB) radio use according to UWB research, development, and business after it established regulatory requirement for communication uses for 3.4-4.8GHz, 7.25-10.25GHz in 2006, and collision avoidance radar uses for 22-29GHz in 2013. While UWB communication and sensing systems have been restricted indoor in Japan, the rest of world have been developing them to a lot of outdoor uses. Lately in this IoT era, wide variety of UWB radio uses have been expected in Japan as well as in a world and demand for UWB radio outdoor use has been increasing while keeping transparency with other nations.

The Major Changes are as follows:

- Bandwidth, Occupied, and Impermissible Emission Available Outdoor
  Channel 9 of IEEE802.15.4aTM with central frequency 7987.2GHz and bandwidth 499.2MHz out of high band 7.25-10.25GHz has been considered to be available outdoor.

- EIRP(Equivalent Isotropically Radiated Power)
  Japanese regulatory requirement for UWB radio has been regulated by emission power, antenna gain as well as EIRP. For the sake of international compatibility, Japanese regulation for UWB radio uses could be regulated by EIRP.

A.1 Radio uses in the frequency band 6.57-10.25 GHz

The detailed illustration of the frequency band is shown in Figure A.1. Red lines indicate channels defined by IEEE802.15.4a, and available band is 7.587-8.4GHz. Blue dotted line systems should be protected for coexistence with such as fixed micro wave communication, satellite, radio astronomy and VLBI etc.

A.2 Update of emission power regulation in case of low gain antenna

Recently demand of small wireless terminals including UWB terminals drastically. A small terminal cannot perform desired covering range because antenna gain of small terminals is used not to be sufficient. Corresponding to the demand, it is permitted that under the range of the regulated Equivalent Isotropically Radiated Power (EIRP), antenna gain can be increased according to attenuation amount of emission power. Increase of emission power can be replaced with attenuation of transmitted antenna gain.

In current regulation, it is permitted that under the limit of the regulated EIRP, antenna gain can be increased according to attenuation amount of emission power. In new regulation, it is permitted that under the range of the regulated EIRP increase of emission power is allowed in case that antenna gain is small to reach the regulated EIRP. The concept of the difference is described in Figure A.2.

A.3 Major Technical Requirement for Outdoor UWB Systems

Major technical requirements for outdoor UWB system are summarized in Table A.3 and Figure A.3. Concurrent requirements for indoor high-band are also summarized for comparison.

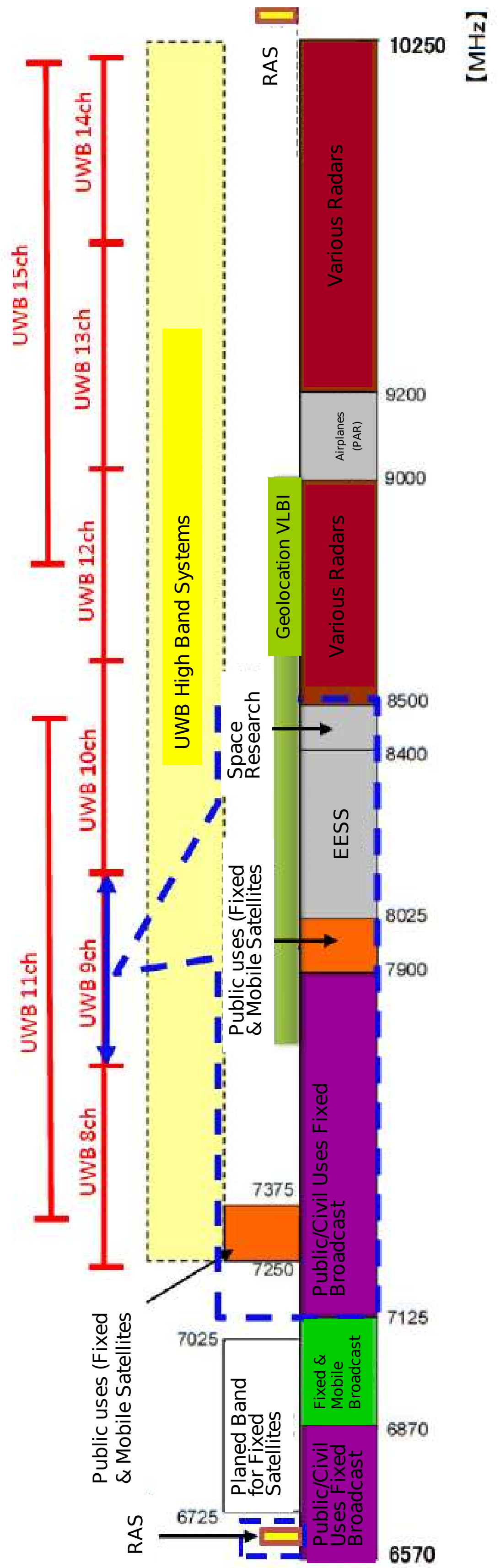

Figure A.1 Radio Uses in the Frequency Band 6.57-10.25 GHz

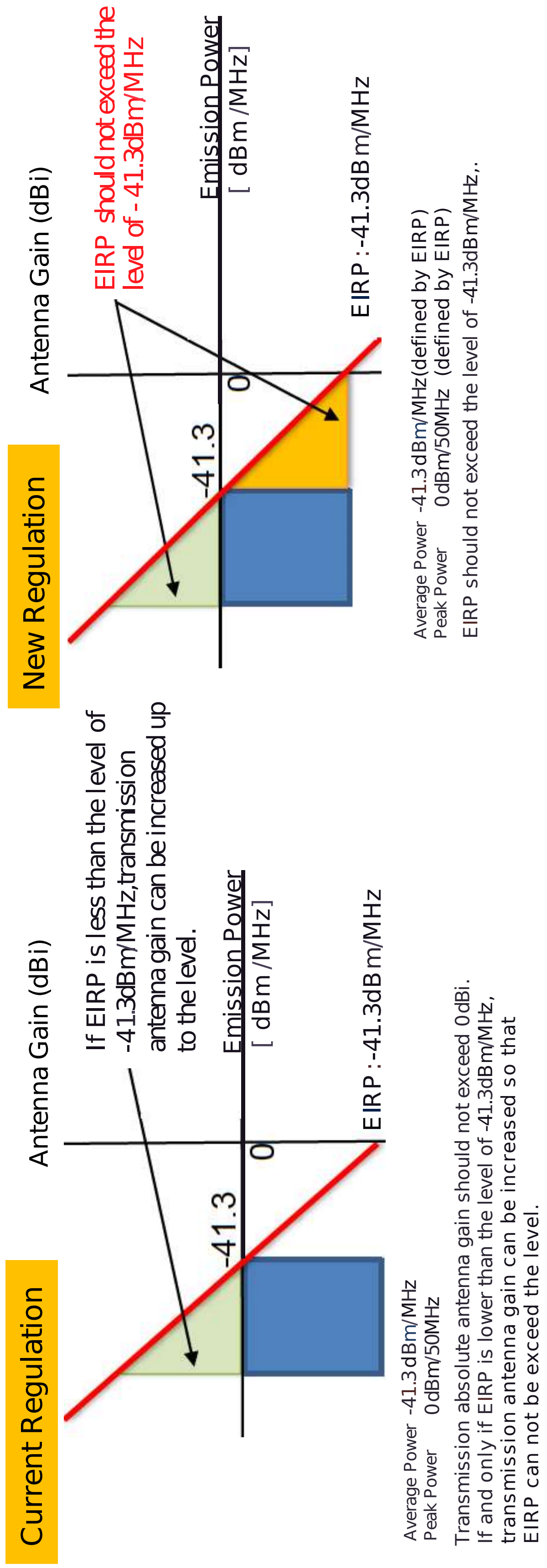

Figure A.2 Update of emission power regulation in case of low gain antenna

Table A.1 Major Technical Requirement for Outdoor UWB Systems

		Indoor high band UWB systems	Outdoor UWB systems
Permissible variance of Band		7.25 - 10.25 GHz	7.587 - 8.4 GHz
Emission power	Average EIRP	<-41.3 dBm/MHz	7.587 - 7.667 GHz : <-51.3 dBm/MHz 7.662 - 8.400 GHz : <-41.3 dBm/MHz
	Peak EIRP	0 dBm / 50 MHz	Peak EIRP No change
Antenna absolute gain		0 dBm	No regulation
Permissible occupied bandwidth		3 GHz	813 MHz (Specific band)
Permissible spread bandwidth		>450 MHz (10 dB bandwidth)	No change
Limits of emission on power subsidiarity (by EIRP)	<7.25 GHz	<1.600 GHz : -90.0 dBm/MHz 1.600 - 2,700 GHz : -85.0 dBm/MHz 2,700 - 7.25 GHz : -70.0 dBm/MHz	No change
	7.25 - 10.25 GHz	-59.3 dBm/MHz	7.25 - 7.587 GHz : -59.3 dBm/MHz 7.587 GHz - 8.4 GHz : -54.0dBm/MHz 8.4 - 8.5 GHz : -59.3 dBm/MHz 8.5 - 10.25 GHz : -60.0 dBm/MHz
	>10.25 GHz	10.25 - 10.6 GHz : -70.0 dBm/MHz 10.6 - 10.7 GHz : -85.0 dBm/MHz 10.7 - 11.7 GHz : -70.0 dBm/MHz 11.7 - 12.56 GHz : -85.0 dBm/MHz >12.56 GHz : -64.0 dBm/MHz	No change

		Indoor high band UWB systems	Outdoor UWB systems
Limits of permitted emission (by average power, EIRP)	<7.25 GHz	<1.600 GHz : -90 dBm/MHz 1.600 - 2.700 GHz : -95.0 dBm/MHz 2.700 - 7.25 GHz : -70 dBm/MHz	No change
	7.25 - 10.25 GHz	N/A	7.25 - 7.587 GHz : -59.3 dBm/MHz 7.587 - 8.4 GHz : N/A 8.4 - 8.5 GHz : -59.3 dBm/MHz 8.5 - 10.25 GHz : -60.0 dBm/MHz
	>10.25 GHz	10.25 - 10.6 GHz : -70.0 dBm/MHz 10.6 - 10.7 GHz : -85.0 dBm/MHz 10.7 - 11.7 GHz : -70.0 dBm/MHz 11.7 - 12.75 GHz : -85.0 dBm/MHz >12.75 GHz : -70.0 dBm/MHz	No change
Limits of permitted emission (by peak power, EIRP)	<7.25 GHz	<1.600 GHz : -84 dBm/MHz 1.600 - 2.700 GHz : -79.0 dBm/MHz 2.700 - 7.25 GHz : -64 dBm/MHz	No change
	7.25 - 10.25 GHz	N/A	7.25 - 7.587 GHz : -35.0 dBm/MHz 7.587 - 8.4 GHz : N/A 8.4 - 8.5 GHz : -35.0 dBm/MHz 8.5 - 10.25 GHz : -35.7 dBm/MHz
	>10.25 GHz	10.25 - 10.6 GHz : -64.0 dBm/MHz 10.6 - 10.7 GHz : -79.0 dBm/MHz 10.7 - 11.7 GHz : -64.0 dBm/MHz 11.7 - 12.75 GHz : -79.0 dBm/MHz >12.75 GHz : -64.0 dBm/MHz	No change
Note		Package should not be easily opened.	

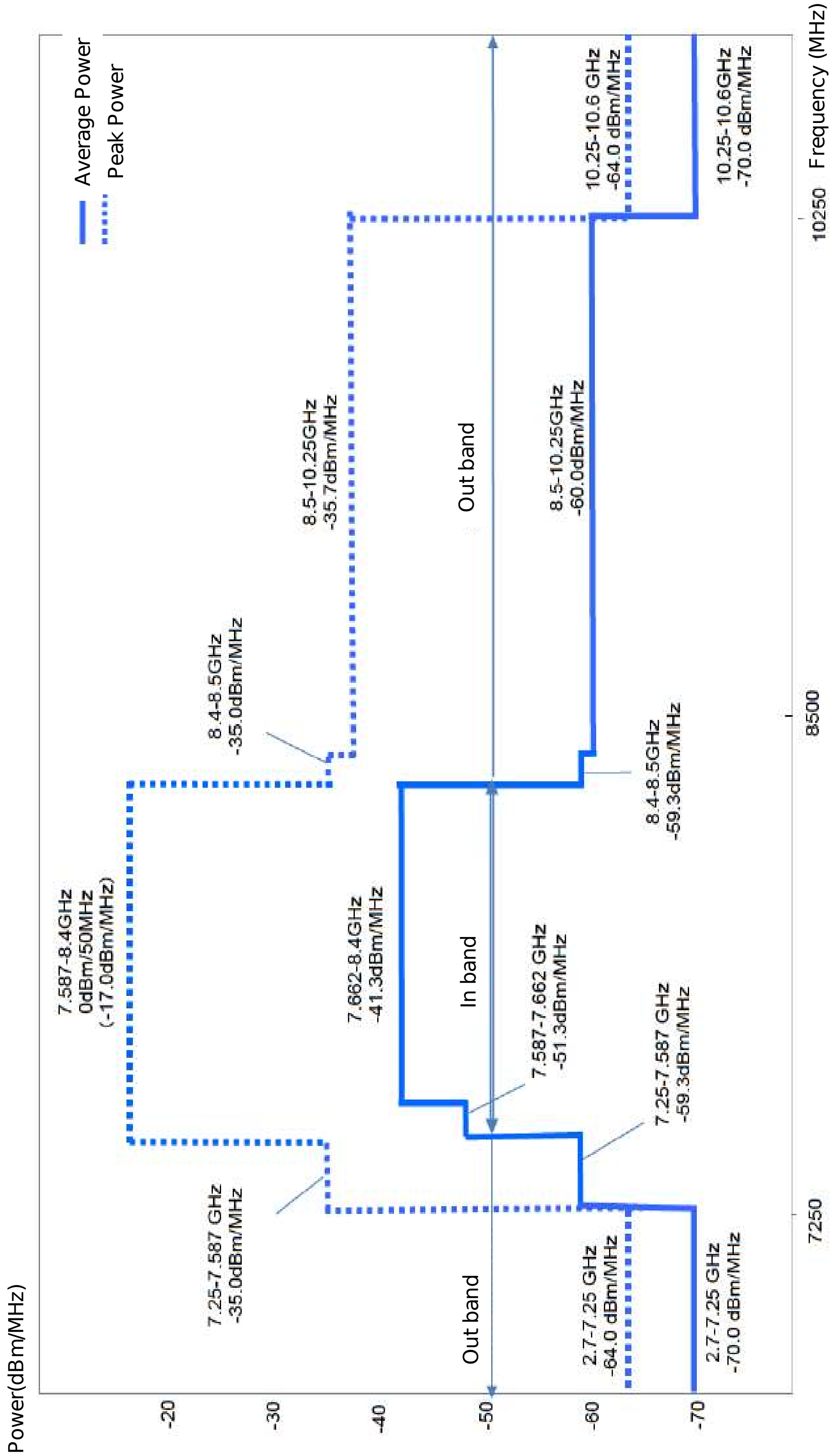

Figure A.3 Major Technical Requirement for Outdoor UWB Systems

Published Papers

Reviewed Journal Papers

(1) Minsoo Kim and Ryuji Kohno, "Transmission Power Margin Control of the Secondary UWB-WBAN to Suppress the Interference to the Primary Cellular Networks Below the Permissible Level Using Integrated Terminal for Both Networks," (to be submitted.)

(2) Minsoo Kim and Ryuji Kohno, "Cognitive Control of Sequence Length to Ensure Secondary UWB-WBAN Performance while Avoiding the Interference to the Primary Cellular Networks Below the Permissible Level Using Integrated Terminal for Both Networks," MDPI Sensors (to be submitted.)

(3) Minsoo Kim, Takumi Kobayashi, Chika Sugimoto, and Ryuji Kohno, "Transmission Power Control of UWB-WBAN for Avoidance of Interference to Cellular Networks Using Integrated Terminal for Both Networks," International Journal of Computer Science and Telecommunications (ICJST) ISSN 2047-3338, Vol.11, Issue.2, pp.8-15, Mar. 2020.

IEICE Annual Conference Letters

(1) Minsoo Kim, Chika Sugimoto and Ryuji Kohno, "Cell Allocation for Interference Avoidance Using Array Antenna," 2012 IEICE General Conference, B-8-9, PP.151 Sep. 2012 (in Japanese)

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