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Transmission Power Control of UWB-WBAN for Avoidance of Interference to Cellular Networks Using Integrated Terminal for Both Networks

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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 paper 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).**

***Index Terms*—Body Area Network (BAN), Cellular Network, Cognitive Radio (CR), Detect and Avoid (DAA), Integrated Terminal, Interference Mitigation, Transmit Power Control (TPC), Ultra-Wideband (UWB)**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) radio systems operate in a microwave wide frequency band, some of which overlap with frequency bands already allocated to existing radio systems such as 3G, 4G, and 5G cellular networks [1]. Therefore, coexistence strategies should be considered to ensure the performance of existing licensed wireless system [2], [3]. For example, regulations in some regions including those of EU and Japan mandatorily require the detect and avoidance (DAA) procedure, which puts UWB systems under obligation to detect the presence of other systems in the overlapped frequency band, and to restrict their transmission power spectral density by -70 dBm/MHz if present or -41.3 dBm/MHz if not present [4].

Various coexistence strategies have been studied [5], [6], 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 has been already available in practice. The aim of this study is to control the transmission power of the UWB system accurately cognitive to coexistence 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.

This paper is organized as follows: In section II, the coexistence scenario of UWB system with cellular system and the conventional coexistence strategies are described. The concept of the Integrated Terminal is also introduced in this section. In section III, the proposed algorithm is presented. In section IV, the performance of the proposed algorithm is evaluated. Section V concludes this paper.

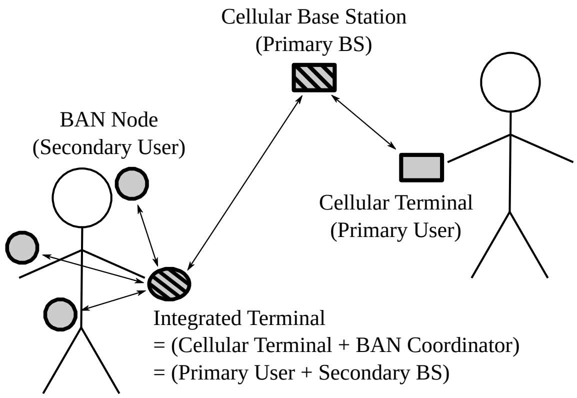


Fig. 1. Coexistence scenario of the UWB and cellular networks

II. COEXISTENCE SCENARIO AND CONVENTIONAL COEXISTENCE STRATEGIES

A. Coexistence scenario and the Integrated Terminal

We consider a scenario where a UWB system based on IEEE 802.15.6 Wireless Body Area Network (BAN) [7] coexists with cellular networks. This scenario is illustrated in Fig. 1.

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 cellular network, e.g. 4G, 5G and local 5G.

Since the information measured by each BAN node is 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 (IT). An IT can join a cellular network as a cellular terminal, and control a BAN, i.e., a UWB network as a BAN coordinator at the same time. In practice, like a smartphone with Bluetooth, a cellular terminal may be commercialized with a UWB module. In fact, we can apply this scenario to iPhone 11 and 11 Pro.

B. Conventional coexistence strategies and their limitations

From a cognitive radio perspective [8], a cellular network is a licensed primary system, and therefore a secondary system, a UWB network, should not interfere with the communication of the cellular network. However, the UWB network spatially overlaps with the cellular network, and inevitably, the signal transmitted by the UWB terminal becomes an interference signal in the context of the cellular network terminal, degrading the performance of the cellular network. Under such circumstances, various regulations are applied to the UWB system in order to protect the communication of the cellular network.

1) Transmit power restriction

The most typical regulation is on the transmission power. UWB devices shall not emit radio waves above a specified spectral mask. The best-known FCC mask [9] is shown in Table I.

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 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.

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 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 [4].

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.

Besides the discussion of whether the value of the upper power limit is appropriate, there are further discussions about DAA. 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

TABLE I
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

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.

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

III. PROPOSED ALGORITHM

In this section, 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 IT, is described.

A. Formulation of system model

To begin with, we formulate the system model of the coexistence scenario illustrated in Fig. 1. The number of cellular terminals is *M*, and that of UWB terminals is *N*. Note that *M* is a number including the IT. We denote the downlink transmit power of the BS for the *i*th cellular terminal as P_i^{pri}, and the channel gain from BS to *i*th cellular terminal as α_i^{pri}. Meanwhile, the uplink transmit power of the *j*th 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 *i*th cellular terminal and the *j*th 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 *i*th 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 *i*th cellular terminal when the *j*th UWB terminal transmits its signal is given by the following equation:

$$\gamma_i^{\mathrm{pri}} = \frac{P_i^{\mathrm{pri}} \alpha_i^{\mathrm{pri}}}{P_j^{\mathrm{sec}} \alpha_{i,j}^{\mathrm{cross}} + \nu_i^{\mathrm{pri}}}, \quad (1)$$

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

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:

$$\gamma_i^{\mathrm{pri}} \ge \gamma_{\mathrm{th}}^{\mathrm{pri}}. \quad (2)$$

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

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

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

B. Transmission power control algorithm using the Integrated Terminal

Most of the parameters appearing in (3) are those of the cellular network, which are unknown to the *j*th 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 IT, and exploits them to determine the transmit power of the UWB terminal. The proposed algorithm uses the cellular module of IT, 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.

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 Fig. 2.

1) Initialization

A BAN coordinator broadcasts beacons i.e, control signals for synchronization. The IT sends the control signal including an initial value of the transmit power P_j^{sec} for the UWB terminals in the network (Fig. 2a), and each UWB terminal sets its own transmit power accordingly (Fig. 2b). The initial value should be determined to a value that satisfies the existing regulations, such as spectrum mask.

2) Transmission

When a packet is generated in the UWB terminal (Fig. 2c), the UWB terminal sends its packet to the IT, which is the BAN coordinator, at the transmission power determined in the previous step (Fig. 2d). At this time, the signal from the UWB terminal appears as interference in the cellular terminal (Fig. 2e).

3) Interference monitoring

Cellular terminals monitor the interference received from UWB terminals for a predetermined amount of time Δt, and deliver this value to to the IT. 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 *i*th cellular terminal $y_i^{\mathrm{I}}(t)$ at time *t*, due to the interference from a UWB terminal can be expressed

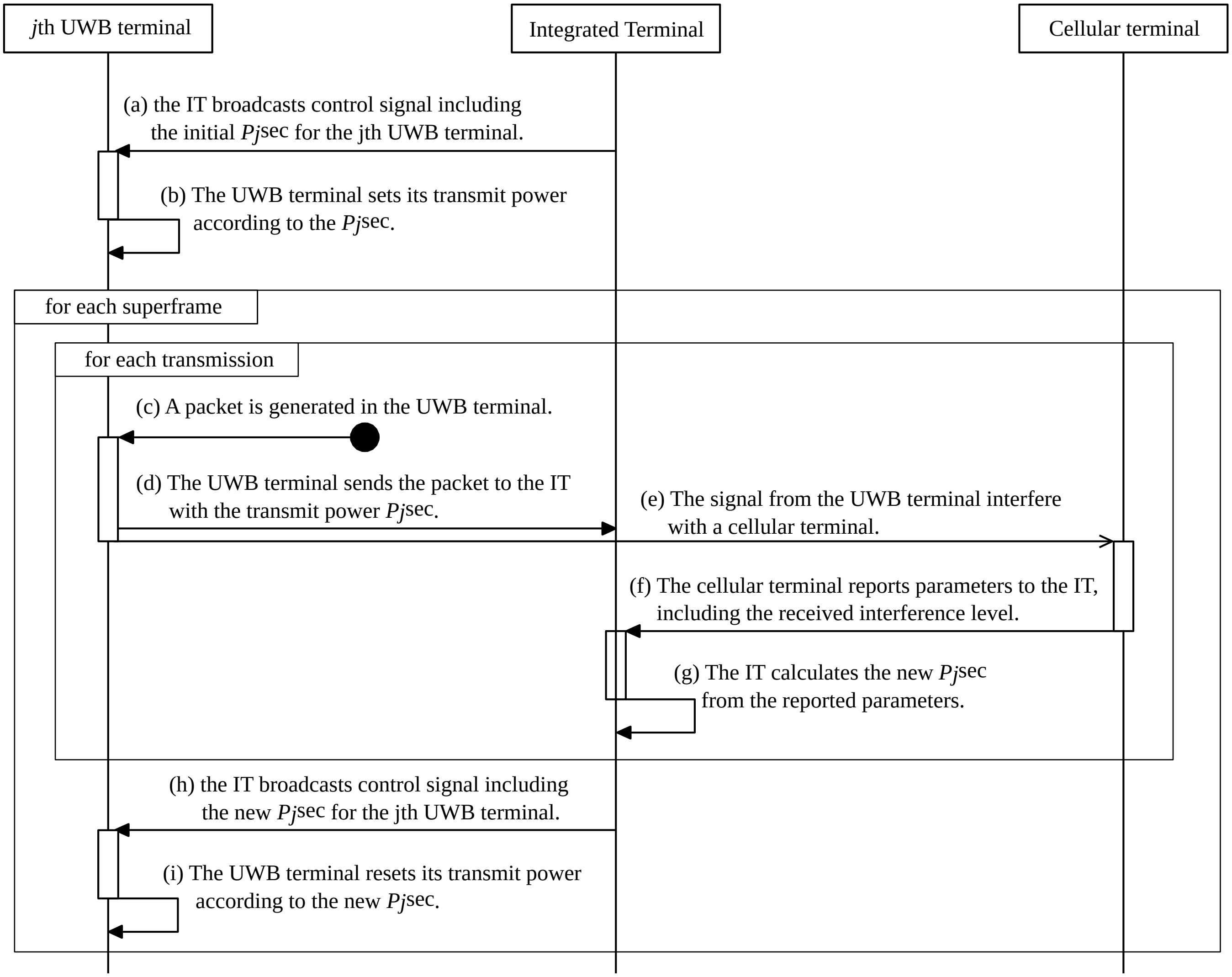


Fig. 2. The sequence diagram of the proposed algorithm

by the following equation:

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

where $\delta_j^{sec}(t)$ 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. $u_j^{sec}(t)$ denotes a pulse shape used by the jth UWB terminal, and $n_i^{pri}(t)$ denotes noise observed at the ith cellular terminal.

As explained in section III-A, we assume that only one UWB terminal transmits its signal during Δt with an appropriate access control scheme (hence $\sum_j^M \delta_j^{sec}(t) = 1$.) In addition, for the sake of simplicity, we assume that P_j^{sec}, $\alpha_{i,j}^{cross}$, and $\delta_j^{sec}(t)$ 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:

$$\begin{aligned} E_i^{I} &= \int_{\Delta t} \{y_i^{I}(t)\}^2 dt \\ &= P_j^{sec}\alpha_{i,j}^{cross} \int_{\Delta t} \{u_j^{sec}(t)\}^2 dt \\ &+2\sqrt{P_j^{sec}\alpha_{i,j}^{cross}} \int_{\Delta t} u_j^{sec}(t) n_i^{pri}(t)\, dt \\ &+ \int_{\Delta t} \{n_i^{pri}(t)\}^2 dt \end{aligned} \qquad (5)$$

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

The integral of the first term in (5) 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 (5) can be regarded as zero, because the pulse and noise are uncorrelated. The integral of the third term in (5) represents the energy of the noise, and can be expressed as $\nu_i^{pri}\Delta t$. Thus, the interference power received by the ith cellular terminal P_i^{I} can be expressed as follows:

$$P_i^{\mathrm{I}} = E_i^{I} / \Delta t$$
$$= P_j^{\mathrm{sec}} \alpha_{i,j}^{\mathrm{cross}} + \nu_i^{\mathrm{pri}}, \quad (6)$$

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

The *i*th cellular terminal reports P_i^{I} to the IT as its received interference level from the UWB terminal (Fig. 2f), along with the signal level of the desired signal from the cellular BS P_i^{S} $\left(= P_i^{\mathrm{pri}} \cdot \alpha_i^{\mathrm{pri}}\right)$ and the desired SINR $\gamma_{\mathrm{th}}^{\mathrm{pri}}$.Various commu-- nication techniques can be considered for a cellular terminal to share these parameters with an IT. For example, a cellular terminal may pass parameters directly to an IT 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 IT.

4) *Transmission power updating*

Since the IT acquires the value of the received interference power at the *i*th 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 *i*th cellular terminal and the *j*th UWB terminal $\alpha_{i,j}^{\mathrm{cross}}$ as follows:

$$\alpha_{i,j}^{\mathrm{cross}} = \frac{P_j^{\mathrm{sec}}}{P_i^{\mathrm{I}} - \nu_i^{\mathrm{pri}}} \quad (7)$$

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

Then, the new transmit power for the *j*th UWB terminal $\hat{P}_j^{\mathrm{sec}}$ is calculated from (3) as follows (Fig. 2g):

$$\hat{P}_j^{\mathrm{sec}} \leq \frac{P_j^{\mathrm{sec}}}{P_i^{\mathrm{recv}} - \nu_i^{\mathrm{pri}}} \left(\frac{P_i^{\mathrm{pri}} \alpha_i^{\mathrm{pri}}}{\gamma_{\mathrm{th}}^{\mathrm{pri}}} - \nu_i^{\mathrm{pri}} \right) \quad (8)$$

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

TABLE II
SUMMARY OF SIMULATION SPECIFICATIONS

Parameters	Values
center frequency	3.4 GHz
permissible interference level of cellular terminal	-114.8 dBm/MHz3
channel environment	free space propagation

Finally, the IT broadcasts a control signal containing the new transmit power $\hat{P}_j^{\mathrm{sec}}$ (h). The UWB terminal also resets its transmit power accordingly (Fig. 2i).

IV. PERFORMANCE EVALUATION

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 II.

- 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

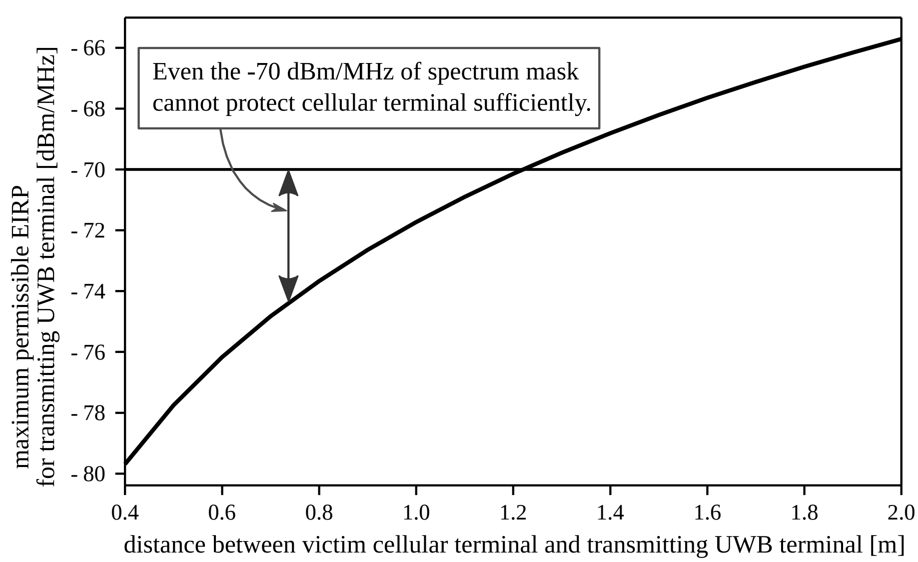


Fig. 3. Maximum permissible transmission power for a UWB terminal

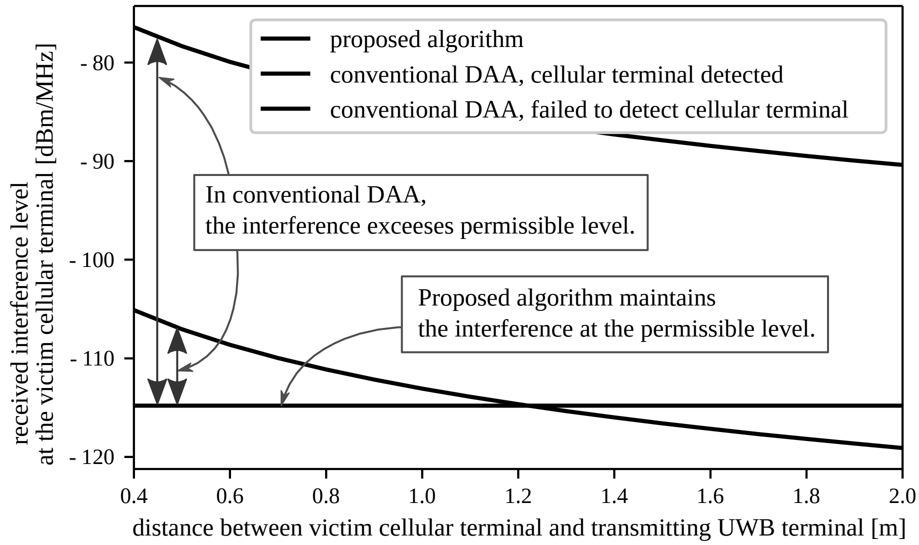


Fig. 4. Interference level at the victim cellular terminal

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 [10].

- 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.

A. *Interference to cellular networks*

The maximum permissible transmission power for a UWB terminal placed at given distances from the victim cellular terminal is shown in Fig. 3. 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.

Fig. 3 explains that the closer the distance to the cellular terminal is, the smaller the power the UWB terminal can transmit without interfering with the cellular terminal beyond the permissible level. 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 a UWB terminal not using DAA, interference cannot be sufficiently avoided.

Fig. 4 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 Fig. 4, 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 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 Fig. 3, 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.

B. *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 a 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.

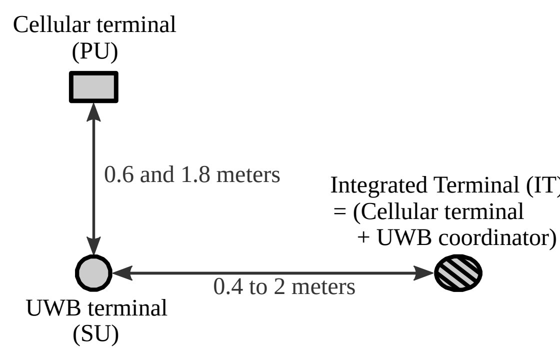
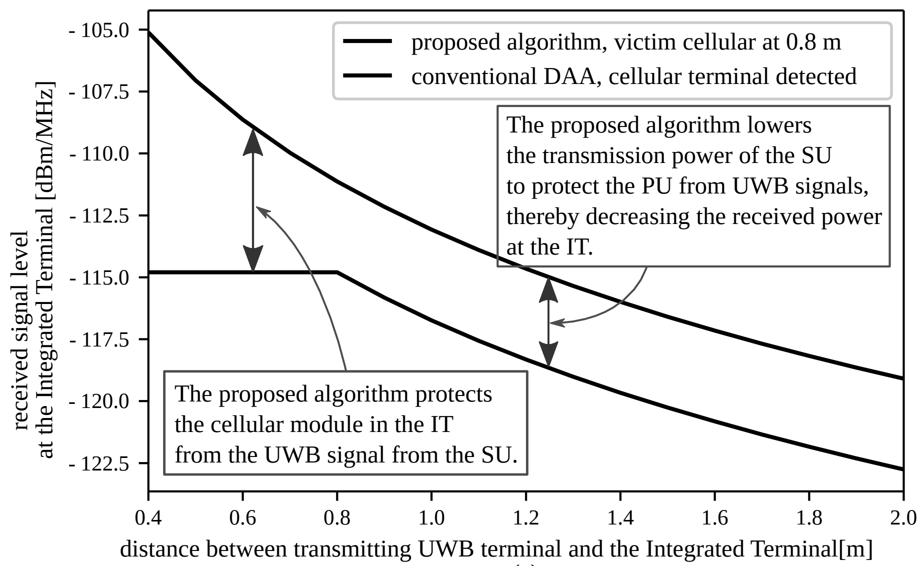
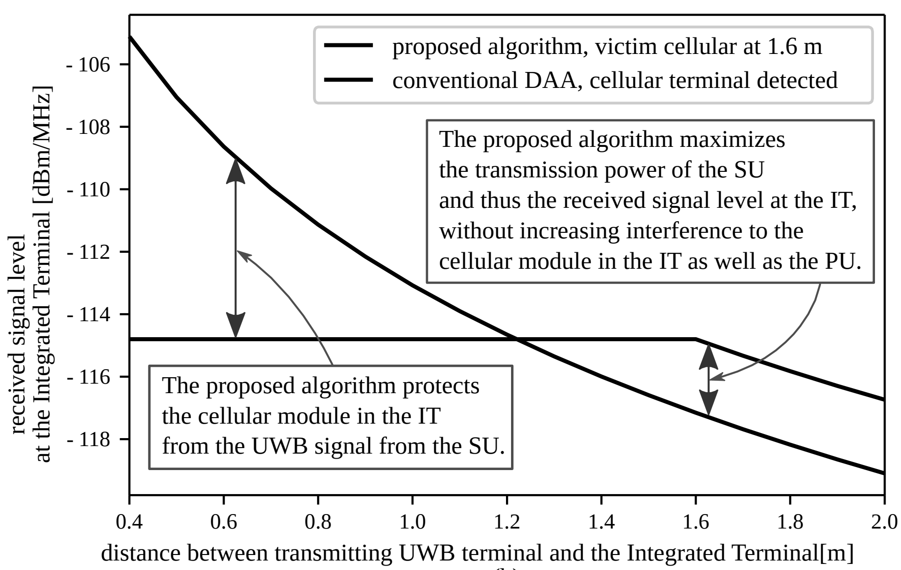


Fig. 5. Layout of the terminals



(a)



(b)

Fig. 6. Received signal level at the Integrated Terminal, in which distance between victim cellular terminal and transmitting UWB terminal is (a) 0.8 m and (b) 1.6 m

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. Fig. 5 describes the layout of the terminals used in this simulation.

Received signal level of UWB signal at the UWB module in the IT is shown in Fig. 6. 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.

Fig. 6 (a) 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 beyond the permissible level to the cellular network, which is a top priority for the proposed algorithm.

Fig. 6 (b) shows a case where the distance between the victim cellular terminal and the transmitting UWB terminal is 1.6 m. Similarly, to (a), 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 a UWB terminal with power of -70 dBm/MHz using the conventional DAA method is attenuated below the permissible interference level. The same result can be seen even if the victim cellular terminal is closer than the integrated terminal from the transmitting UWB terminal.

V. CONCLUSION

We have presented 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. 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. Although this paper has shown this through simulation results of transmission power rather than throughput, 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.

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. 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.

We would like to mention the possible drawbacks of this proposed method. 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, 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 our future work to include the estimation error and overhead in the algorithm to increase the reliability of the proposed method.

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