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Overview of Research, Development, Standardization, and Regulation Activities in NICT UWB Project

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SUMMARY  This paper presents an overview of research, development, standardization and regulation activities on ultra wideband (UWB) technologies in National Institute of Information and Communications Technology (NICT). NICT started a project on UWB technologies since 2002, and organized UWB consortium in cooperation with more than 20 companies and 7 universities in Japan. Up to now, we have been conducting numerous UWB R&D including the following main works: i) key technology development such as MMIC chips, antennas and other devices, ii) measurement and channel modeling for UWB signal propagation, iii) standardization in international activities of IEEE 802.15, ITU-R TG1/8 as well as in a national regulatory committee of Ministry of Internal Affair and Communications (MIC). The UWB systems we have studied occupy frequency bands range from microwave band (3–5 GHz) to quasi-millimeter wave band (24–29 GHz). Various prototype UWB systems including multi-functional terminals have been developed. The output of NICT has been succeeded by industrial parties with national and international standardization and regulation.

key words: UWB, soft spectrum adaptation (SSA), coexistence, detection and avoidance (DAA), spectrum mask, ITU-R TG1/8, radar

1. Introduction

The approval of commercial use of ultra-wideband (UWB) technology in 2002 by the Federal Communications Commission (FCC) in USA [1] initiated the tide of R&D on UWB all over the world. Since its inherent capability of providing high data rate communication and high precision ranging, UWB is regarded as one of the main technologies in supporting ubiquitous wireless systems. In order to take a leading role in UWB R&D, NICT set up the UWB Technology Institute at Yokosuka Radio Communications Research Center in September 2002. The main activities of NICT’s UWB Technology Institute are illustrated in Fig. 1. NICT had a lot of UWB technology research goals, i.e., a)optimization of both communication schemes and protocols with regard to communication and ranging, b)implementation of circuits and devices including antennas, that generate shaped pulses with soft spectrum adaptation (SSA), c)study on propagation characteristics and measurement of UWB signals with wide-frequency bandwidth and lower power, and d)study on interference and coexistence of UWB systems with other radio systems sharing the same frequency band.

For the purpose of conducting UWB R&D more efficiently and smoothly, the NICT UWB consortium was established in October 2002. The consortium was organized by NICT with more than 20 private companies and 7 universities to conduct joint R&D on UWB. Various UWB research facilities and instruments (e.g., UWB testbed, UWB testroom, etc.) are provided and used for its activity.

Besides the intensive R&D efforts on UWB technologies, we have been actively taking part in the UWB international standardization. We have made a large number of proposals and done a great deal of work in both task groups of TG3a and TG4a in the working group of IEEE802.15 for wireless personal area network (WPAN). All proposals made were based on the outcome of our R&D results in collaboration with academia and industry. Moreover, we also played an important role in ITU-R TG1/8, which is a working group to do recommendation for international UWB regulation.

This paper summarizes the R&D, standardization, regulation and other activities in the NICT UWB project. The following section overviews the R&D outputs, which have been mainly made by NICT UWB consortium. Then, our contributions in the standardization for IEEE802.15 and ITU-R TG1/8 are summarized in Sect. 3. Regulatory activities are introduced in the Sect. 4.
2. R&D Activity by NICT UWB Consortium

This section outlines R&D activities in the NICT UWB consortium. The activities cover wide research area including pulse shape technology, propagation measurement for channel modeling, implementation of MMIC chips and antennas, developments of multi-functional devices etc.

2.1 Soft-Spectrum Adaptation (SSA)

SSA [2]–[4] has been proposed as a UWB technology that can be applied to detection-and-avoidance (DAA) functionality [5]. As providing DAA functionality is important for successfully implementing regulation-compliant UWB devices, we developed SSA, which is a set of design criteria on pulse waveform. SSA uses spreading and shrinking of the frequency bandwidth of UWB waveforms, which is adaptable and controllable, as shown in Fig. 2. Using the concept of SSA, required pulse waveforms, which cause no interferences with existing radio systems, can be achieved.

We have developed a UWB testbed to evaluate PHY technologies based on SSA. There are photographs of the transmitter and receiver of the UWB testbed in Fig. 3. The transmitter is based on a 4-bit/10G-Sample digital-to-analog converter (DAC) that generates various UWB signals. Using this signal generator, it is possible to generate UWB signals for pulse-position modulation (PPM), bi-phase modulation, direct sequence-UWB (DS-UWB), and pulse-shape modulation (PSM). The receiver consists of a band pass filter (BPF) (3.1–5.0 GHz), a low-noise amplifier (LNA), an 8-bit/20GS analog-to-digital converter (ADC), and a digital signal processor (DSP). The DSP is for correlation demodulation, which is carried out using a template UWB signal. The demodulation results are input into a PC via Ethernet to monitor the bit error rate, throughput, and so on.

We also investigated channel coding and decoding technique suitable for SSA-based UWB communication systems. Channel coding plays an important role in UWB systems because its signal-to-noise ratio of the received signal is low. We invented a decoding technique that can be applied to any combination of SSA-based modulation and coding, called combined iterative demapping and decoding (CIDD) [6].

2.2 Measurements and Modeling of UWB Channels

We focused on developing antenna-independent channel models, but introduced a UWB signal to achieve fine temporal resolution. We made double direction channel measurements of a line-of-sight (LOS) and none-line-of-sight (NLOS) propagation environment with UWB signals.

Haneda et al. [7] developed a UWB channel sounder together with a parametric channel parameters estimation algorithm. Measurements from an anechoic chamber demonstrated that the sounder is capable of resolving closely spaced paths in the angular-temporal domain. Measurement example shows that the sounder realizes 10 deg and 0.67 ns resolution in azimuthal angle and time difference, respectively. In addition, the parametric channel estimator can derive frequency-dependent magnitude and phase of each path. Furthermore, the authors have shown that the accuracy of the parameter estimation algorithm improves by introducing spherical wavefront of impinging paths. The paper contributes in providing a closer and accurate look of indoor propagation channels with an emphasis on physical phenomena.

Haneda et al. [8] then applied the sounder for modeling propagation channels in a standard Japanese wooden house. The authors performed the double-directional sounding in a LOS scenario. In the sounding, the dominant propagation paths were first identified as shown in Fig. 4. The authors also found that the propagation paths traveled in a “cluster” (see Fig. 5), and investigated its angular-temporal properties. Results revealed that the root mean square angular and delay spreads varied from 1.5 to 5.0 deg and from 0.1 to 0.4 ns, respectively, depending on clusters. Further analyses were performed to yield scattering loss of each cluster, resulting in around 10 dB on average. The paper is meaningful in presenting UWB cluster parameters based on physical structures of indoor environments.

Sato and Kobayashi proposed a new path loss formula...
of UWB LOS propagation [9]. This formula is based on the narrowband two-path (direct and ground reflected waves) model, taking into account the bandwidth of signals. The following results were derived from numerical calculations: (1) UWB signals suffer less interference fading than narrowband signals; (2) UWB path loss exponents approximately change to 2 to 4 around the breakpoint; and (3) the breakpoint distance depends on the transmitting and receiving antenna heights, the lowest frequency, and the bandwidth of the signal.

2.3 Implementation

The NICT UWB consortium has fabricated microwave monolithic integrated circuits (MMICs) using 0.18-µm CMOS technology, including either the RF part of the multiband OFDM (MB-OFDM) [10] or impulse radio based UWB system. Feasible antennas with a wideband flat gain have been developed for the microwave-band UWB systems.

We developed an MMIC that can be used to evaluate MB-OFDM systems (Fig. 6) [11],[12]. This MMIC contains all the RF devices that are required for MB-OFDM systems. We implemented a switched trans-conductor mixer for the topology on the up-conversion mixer, to achieve low power dissipation and wide-band characteristics. The power dissipation of this mixer is 4.3 mW at a 1.3-V supply voltage. The mixer can still operate when the bias voltage is decreased to 0.7 V. A frequency-hopping synthesizer, which can switch the center frequency among 3.5, 4.0, and 4.5 GHz within 5 ns, was also implemented. We achieved 300-Mbps data transmission at a distance of 3 m by using this MMIC.

We also fabricated an MMIC chip for impulse radio based UWB systems [11] (Fig. 7), suitable for low-rate or location awareness applications. This MMIC contains a pulse generator, a BPF, an LNA, and a mixer. We achieved 300-Mbps data transmission at a distance of 3 m by using this MMIC.

NICT has developed various UWB antennas suitable for the microwave band, from 3.1–10.6 GHz. One of these is the printed bow-tie antenna [13] shown in Fig. 8. This antenna provides omni-directional pattern for the lower frequency UWB band, i.e., 3.1–5.1 GHz. The size of this antenna on the FR-4 substrate is small and thin, as can be seen from Fig. 8. We have invented another kind of antenna, which is based on multi-resonant architecture [14]. This antenna eliminates a specific frequency bandwidth by
setting its resonant points appropriately. Therefore, it plays the roles of a UWB antenna as well as a band-elimination filter.

2.4 Multi-Functional Devices Using Millimeter Wave Band UWB

The NICT UWB consortium has three task groups (TGs) for R&D on multi-functional devices in 26-GHz-band UWB systems [15]. The multifunctional devices provide a wireless-communication as well as radar-ranging function. The target specifications for each TG’s activities, from the viewpoint of target environment, data rate, and ranging accuracy are summarized in Table 1. This section gives a brief introduction to these TGs.

2.4.1 TG1 for Outdoor Low-Rate Data Transmission and Precision Ranging

Short-range radar (SRR) for automobiles using 26 GHz-band UWB is an attractive application. TG1 investigated a multi-functional UWB system where target applications for this system include collision avoidance in parking areas, as shown in Fig. 9. In this application, UWB signals that contain a warning message are transmitted to approaching cars, i.e., wireless communication. In addition, the UWB signals are used to detect the approaching car by radar-ranging function. Then, we call it multi-functional UWB devices. To create such multi-functional UWB system for practical use, we developed a carrier-leak-free burst oscillator [16], which gives no carrier leakage causing a huge line spectrum at its center frequency.

We also developed a prototype of multi-functional UWB system that provides communication and radar ranging function [17]. Figure 10 is a photograph of the prototype system. This prototype’s radar-ranging function achieves a detection error of less than 10 cm at a distance of 5 m. Its communication function achieves a 100% packet arrival rate at a distance of 10 m.

2.4.2 TG2 for Indoor High-Rate Data Transmission and Precision Ranging

The main target of TG2 is to evaluate the capability of multi-functional UWB systems to provide high-speed WPAN and location awareness in indoor environment. Figure 11 shows an example of its application, i.e., a high-speed WPAN system with a home security sensor. Here, the UWB system provides high-speed data transmission of more than 1 Gbps. It also provides a radar-ranging function with an accuracy of tens of centimeters. In a case of application at home, this system usually works as a high-speed WPAN; while none is at home, this system works as a sensor to detect intruders. In order to study the availability of such high-speed data transmission in the 26 GHz band, we evaluated BER performance of a 26 GHz-band UWB system through measurement-based simulations [19]. In the simulation, measured channel responses in an office room [18] were used. A binary pulse position modulation (BPPM) was

<table>
<thead>
<tr>
<th>Environment</th>
<th>Data rate</th>
<th>Ranging Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG1</td>
<td>Outdoors</td>
<td>Tens of kbps</td>
</tr>
<tr>
<td>TG2</td>
<td>indoors</td>
<td>Max of 1.5 Gbps</td>
</tr>
<tr>
<td>TG3</td>
<td>Outdoors</td>
<td>Max of 1.5 Gbps</td>
</tr>
</tbody>
</table>
3. Contributions to International Standardizations

The activities in UWB international standardization including IEEE802.15 and ITU-R TG1/8 are summarized.

3.1 IEEE 802.15.3a for High-Rate WPAN

IEEE802.15.3a [20] is the first targeting standard with UWB to provide an alternative PHY for high-rate for existing standard of IEEE802.15.3. NICT submitted a proposal [21] and various technical contributions in TG3a, since March 2003. The main technology of our proposal is SSA, which is a set of criteria for designing UWB waveforms. By using these design criteria on pulse waveforms, we can obtain impulse waveforms that enable coexistence with narrowband wireless services and between UWB systems. We have shown various SSA-based waveforms; Hermitian-based pulse shapes for achieving orthogonality between waveforms, pulse shapes with frequency notches by using a delay line or high-speed DAC, and so on. Also, CIDD, a decoding method for channel coded UWB systems, was proposed as an optional decoding technique to achieve an extra coding gain for TG3a UWB systems [22].

TG3a successfully merged 24 original proposals into two. One is called as multi-band orthogonal frequency division multiplexing (MB-OFDM) [10], which is based on multi-carrier modulation. Another is direct-sequence UWB (DS-UWB), which uses the impulse radio based BPSK modulation [22]. However, TG3a encountered difficulty to further merge the two proposals. As a result, a motion to disband TG3a was adopted in Jan. 2006. UWB standardization for high-rate WPAN is left to other approaches.
3.2 IEEE 802.15.4a for Low-Rate WPAN

IEEE802.15.4a [23] is a targeted standard for low-rate WPAN discussed by task group of TG4a. TG4a was set up one year later than TG3a. However, TG4a has been being in a successful process. TG4a merged 26 formal proposals into one and released the first draft standard in Dec. 2005 and the second draft standard in Apr. 2006. The draft standard has collected a cumulative affirm ratio of 83.6% from IEEE802.15 members. TG4a is currently continuing the works to update the draft toward a final version of the standard. NICT made several important proposals and a lot of contributions at TG4a. Proposals and contributions made by NICT and were adopted in the draft include coding for forward error correction (FEC) [24], band plan [25], pulse waveforms [26], clear channel assessment (CCA) with pilot preambles [27], ranging techniques [28], etc. All these contributions are based on our original researches.

The purpose of TG4a is to provide low data-rate but high precision ranging with low cost and low power consuming devices. Mandatory data rate is 0.8 Mbps while the ranging precision can be smaller than 30 cm. A main application for TG4a is wireless sensor networks (WSN). As an example, a conceptual view of WSN for home security is shown in Fig. 14. UWB nodes with various sensors are deployed in rooms, near doors, or on windows. Various information collected by these sensors are sent through the UWB based WSN to the control unit. Every sensor will also report its position when required using the ranging function provided by UWB. The collected information can then be used for auto lighting, environment control, fire alarm, intruder detection, etc.

3.3 ITU-R TG1/8

ITU-R TG 1/8 [29] was established in July 2002 to study the compatibility between ultra-wideband devices and radiocommunication services. TG 1/8 was divided into four working groups (WGs), i.e. characteristics in WG 1, impact in WG 2, spectrum management framework in WG 3, and measurements in WG 4. TG 1/8 had six meetings until Oct. 2005, and submitted four draft new recommenda-

4. Regulation and Other Activities

4.1 Japanese UWB Radio Regulatory Activities

Japanese regulator Ministry of Internal Affair and Communications (MIC) established a committee on UWB wireless systems on Sept. 30, 2002. Under the main committee five working groups on common operation and on investigating coexistence were established. During Oct. 15, 2002–March 20, 2006, totally 21 working group meetings were held to investigate coexistence problem, technical requirement for legal UWB systems and so on.

The meanwhile, the MIC reported an intermediate report with draft spectral masks for emission power of a UWB transmitter on Feb. 2, 2004 after public comments were collected. The MIC mandated Multimedia Mobile Access Communication (MMAC) Forum in Association of Radio Industries and Businesses (ARIB) to test interference to victim systems during March–Aug., 2005. In the Forum, NICT provided a UWB testbed and experimental fields, and contributed in measurements and analysis of UWB signals with coexisting systems. The MIC reported a latest draft spectral mask with DAA on Aug. 25, 2005 while Conference of European Postal and Telecommunications administration (CEPT) in Europe reported a similar mask with DAA on Sept. 12, 2005. The meanwhile, NICT contributed in collaboration with other nations by establishing MoU (Memorandum of Understanding) with SARA in Europe, UWB Forums in Korea and China and by participating in China, Japan, and Korea (CJK) Workshop on UWB in Seoul on Sept. 27, 2005 [35]. The MIC submitted the Japanese draft spectrum mask to ITU-R TG1/8 in Geneva during Oct. 12–20, 2005.

After the ITU-R TG1/8 meeting, the MIC UWB regulatory committee meetings were held to report evaluation results of the draft spectrum mask for coexistence and to discuss on remained problems and so on. The committee finalized a draft of radio regulation for UWB wireless systems with a spectrum mask on Jan. 31, 2006. After call for public comments for the draft until March 2006, the MIC
approved the draft with minor revision and authorized it as a part of Japanese regulation for UWB wireless systems on March 27, 2006.

4.2 Japanese UWB Radio Regulation Context

Main context of the authorized regulation is summarized below.

4.2.1 General Requirements

1) UWB Definition
The recommendation given by ITU-R SG1 (DNR ITU-R SM.[UWB.CHAR]) is used for UWB definition. At the maximum radiation frequency (FM), the 10 dB-down bandwidth (B-10) must be larger than 500 MHz or the fractional bandwidth must be larger than 20%. Moreover, systems using frequency hopping or chirping are regarded as UWB systems as long as their instantaneous bandwidth meet the above UWB bandwidth definition.

2) UWB Frequency Bands
The frequency bands of 3400 MHz through 4800 MHz and 7250 MHz through 10250 MHz are assigned for UWB operation. For 3400 MHz through 4800 MHz, interference mitigation techniques are required. However, for 4200 MHz through 4800 MHz, interference mitigation techniques are not required until the end of Dec., 2008. UWB systems shall not interrupt other radio systems operated in the same band. UWB systems shall not defer the operation of other radio systems.

3) Transmission Power
Average power and peak power are defined in Table 2. The approved spectrum mask is shown in Fig. 15. In the frequency band 3.4–4.8 GHz, efficient mitigation techniques are required. This mask is only for indoor high-speed communications. Chirp or CS (Continuous Spectrum) waveform is applicable [36].

4) Antenna Gain
Antenna gain must be smaller than 0 dBi. However, if the e.i.r.p. is below the power limit given in Table 2, not reached, a large antenna gain can be applied to reach the limit.

5) Transceiver and Modulation
Transceivers can be simplex, fill-duplex, or semi-duplex. here is no limitation on modulation types.

6) Spread Bandwidth
10-dB bandwidth must be equal to or larger than 500 MHz.

7) Data Rate
The data rate must be equal to or higher than 50 Mbps. However, a lower data rate is permitted in case where the purpose of using the lower data rate if for interference avoidance from noise and noise-like so as to maintain Quality of Service (QoS).

8) Communication Control
i) A UWB transceiver must detect the identification signals from other UWB equipments before start communica-

Fig. 15 Japanese spectrum mask approved in March 2006.

<table>
<thead>
<tr>
<th>Table 2 Radiation power (not e.i.r.p.)</th>
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<tbody>
<tr>
<td>Frequency band [MHz]</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>3400-4800*</td>
</tr>
<tr>
<td>7250-10250</td>
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</tbody>
</table>

* Average power and peak power must be –70 dBm/MHz and –30 dBm/50 MHz if interference techniques are not installed. However, this is not applied for 4200 MHz through 4800 MHz until the end of Dec. 2008.

9) Intervention Avoidance
Functions of sending and receiving identification signal are required. No interventions to other radio systems are allowed.

10) Communications between Equipments within a Same Terminal
i) Equipments using radios must have an identification code with a length larger than 48 bits. ii) Generally, it must detect channel and the link can be established only when the channel is free.

11) Operation Limitation
Operation is limited to indoor. This should be guaranteed by i) A ‘host’ equipment must be connected to an AC power supply. Other ‘client’ equipments are controlled by the ‘host’ and are not necessary to be connected to AC supplies. ii) There must be a clear and easy-to-look note attached to a UWB equipment to remind the indoor operation limitation.

12) Measures for Anti-illegal Re-build
The devices must be built robust and be difficult to dismantle.

13) EMC to Medical Equipments
The impact EMC interference among UWB equipments and electronic medical equipments must be soundly taken into consideration.

4.2.2 Technical Requirements for Radio Equipments

(1) Transmitters
(1-1) Occupied Bandwidth
To be compatible with the existing lab, occupied bandwidth is limited instead of UWB transmission bandwidth. As to the UWB transmitter, it is decided as follows. i) To be smaller than 1400 MHz at 3400 MHz through 4800 MHz. ii) To be smaller than 3000 MHz at 7250 MHz through 10250 MHz. Interference mitigation techniques are required. However, this requirement is not applied for 4200 MHz through 4800 MHz until the end of December, 2008. The permitted bandwidth occupancy is smaller than 600 MHz.

(1-2) Unwanted Emission Level

The unwanted emission level is given in Table 3.

(1-3) Reference Bandwidth

The reference bandwidth for permissible un-intentioned emission is 1 MHz.

(1-4) The Permissible Deviation of Emission Power.

It must be in the scope of smaller than 20%.

(1-5) Emission from Chassis

e.i.r.p. must be smaller than the permitted unwanted emission.

(2) Receive Equipments

For 3400 MHz through 4800 MHz and 7250 MHz through 10250 MHz, the permitted unwanted emission must be smaller than 4 nw per MHz (−54 dBm/MHz). For other frequency band must be below the level determined in Table 3.

4.2.3 Future Modification of Technical Condition

In the above-mentioned technical requirements for coexistence with other wireless systems, some existing systems may be seriously interfered according to distribution of UWB systems in future. Therefore, interference to other wireless systems may be examined and investigated in practical environment. The technical requirements will be examined and modified around three years later considering spread situation of UWB systems, evaluation results of influence to other systems, and an international trend. In case that a UWB system may make a trouble in operation of other wireless systems, it is necessary that a manufacture of UWB systems should actively contribute in avoiding its interference. Corresponding to future change of international frequency allocation in WRC 2007 etc., the technical requirements may be modified.

4.2.4 Future Examination Subjects

Although the MIC authorized a part of UWB wireless systems in March 2006, several remained subjects will be successively taken into account by the MIC as described below.

(1) Successive Examination Subjects

(1-1) Outdoor Usage

i) Since outdoor usage of UWB systems may be demanded, technical requirement for coexistence in outdoor applications may be examined considering spread distribution, international trend and so on. ii) Usage inside an automobile may be also examined.

(1-2) Interference Suppression Technologies

In particular, the band of 3400–4800 MHz is scheduled to apply for the 4th Generation of Mobile Communication Systems in future. Appropriate interference suppression technologies to avoid interference to current and future coexisting systems should be examined carefully with consensus of operators or users of the coexisting systems and manufactures of UWB systems.

(2) New Applications

A low data-rate sensor network in micro wave band, collision-avoidance vehicular radar in quasi-millimeter and millimeter wave band will be taken into account next.

5. Concluding Remarks

This paper summarized R&D, standardization, and regulation activities in NICT UWB project. R&D activities and corresponding outcomes at microwave and millimeter wave bands were introduced. At the microwave band, the MMICs for MB-OFDM and impulse radio absed UWB, UWB antennas, and UWB testbed were described as examples. At quasi-millimeter wave band of 24–29 GHz, various multifunctional UWB systems were overviewed. We have also introduced the results on measurements and modeling of UWB propagation. Our activities in the UWB standardization task groups of TG3a and TG4a in IEEE802.15 and ITU-R TG1/8 were summarized. Regulatory activities in the MIC and a part of regulation authorized in March 2006 were introduced.

We hope that this paper will be useful for researchers, engineers, bureaucrats, businessmen and so on for their study, business, and social services for UWB [37].

Acknowledgments

The authors thank all members who join the NICT UWB project and its coordinated consortium.

References

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[25] I. Lakis and H.-B. Li, “IEEE P802.15-06/059r0: Above 6 GHz Fre-
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