

Improvement of Ultra-wideband Link Performance over Bands Requiring Interference Mitigation in Korea

Ahmad M. Rateb, Syarifah Kamilah Syed-Yusof, and Norsheila Fisal

Ultra-wideband (UWB) systems have witnessed a debate over whether they may cause interference to other existing and future narrowband systems sharing their band of operation. The detect and avoid (DAA) mechanism was developed as a solution to reduce interference to narrowband systems in order to ease regulatory concerns. It works by adaptively reducing the transmitted power at the overlapping bands upon detecting an active narrowband link. However, employing DAA degrades the performance of UWB transmissions. In this paper, we present the Korean UWB regulations as an example of regulations that require DAA in certain bands. We investigate DAA's impact on performance and propose a method to mitigate it, which provides UWB with the more efficient support of the DAA mechanism and enables it to avoid a larger number of narrowband users while sustaining the data rate. Results show significant improvement in performance with the application of our technique compared to conventional performance.

Keywords: Detect and avoid (DAA), ultra-wideband (UWB), coexistence, multiband orthogonal frequency division multiplexing (MB-OFDM).

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I. Introduction

Recently, there has been growing interest in ultra-wideband (UWB) technology [1] as an underlay technology that is able to carry very high data rates over short ranges with transmitted power low enough to be beneath the unintentional interference level, and hence considered as background noise for consumer electronic devices. This makes it the best candidate for realizing wireless personal area networks (WPANs), which require low power, low cost, and a high data rate, for applications such as wireless computer terminals and wireless consumer electronics (for example, the wireless transfer of video from a DVD player to a digital TV).

The enormous band allocated for UWB operation (7.5 GHz in USA and 4.7 GHz in Korea) necessarily overlaps with bands allocated to various wireless systems worldwide, such as digital TV, WiMax, third and fourth generation mobile communications, satellite communication, and various systems deployed for government applications, such as digital broadband radio working in the public safety band [2]. We term all these systems as narrowband (NB) systems referring to their bandwidth compared to that of UWB. On the other hand, the underlay nature of UWB implies that it reuses spectrum pre-allocated to NB systems without affecting their operation. However, despite the very low power constraints, this coexistence issue and its effect on victim narrowband systems have led to a debate between UWB technology promoters and regulatory bodies. As a result, detect and avoid (DAA) mechanisms [3] were proposed to minimize interference caused by UWB on narrowband users, compromising its complexity and performance. DAA operates by continuously detecting the presence of narrowband links and acting to shape their transmitted spectra by minimizing transmitted power in

the conflicting bands. Consequently, DAA technology provides the flexibility needed to enable universal support of regulatory measures and to relax concerns about interference. As a result, DAA has been adopted and required by regulatory bodies in many countries in the EU, Japan, and Korea. However, this comes at the price of degraded UWB performance.

In this paper, we propose a methodology designed to assist UWB devices in adapting to different DAA scenarios they might face. Our methodology is based on an enhancement to the physical layer (PHY) of the UWB transceiver. Because it is the *de-facto* high-speed UWB standard, we tailored our design to the ECMA-368 standard [4] for high-rate UWB issued by the WiMedia alliance [5]. Our enhancement consists mainly of a technique that works to mitigate the negative effects of DAA on UWB transmission through adaptive distribution of data on OFDM tones. This includes a scheme for varying channel coding rates with high flexibility and developing designs for transmitter and receiver that can support our technique.

The remainder of this paper is organized as follows. We provide a brief summary of Korean UWB regulations and an overview on the relevant WiMedia UWB PHY and MAC features in the rest of this section. In section II, we explain the DAA mechanism and approaches to implementing it. In section III, we explain our proposed methodology. Then, in section IV, we provide selected results, discuss their rationale and impact, and show how our work can improve overall performance. We draw our conclusions and make final remarks in section V.

1. UWB Regulations in Korea

In July 2006, Korea's Ministry of Information and Communication (MIC) allocated UWB spectrum as shown in Fig. 1. The Korean UWB spectrum is discontinuous, and allocated as follows [6]:

- 1) From 3.1 GHz to 4.2 GHz: DAA required,
- 2) From 4.2 GHz to 4.8 GHz: DAA requirement waived until June 2010,
- 3) From 7.2 GHz to 10.2 GHz: No interference mitigation required.

As seen in Fig. 1, the DAA-required band overlaps with WiMedia's band group (BG) 1. Therefore, BG1 can fully operate in Korea as long as DAA requirements are fulfilled. BG1 is specifically important, as it is well understood from the basics of wireless communications that lower frequencies attain better obstacle penetration capability and smaller path loss. Hence, BG1 has the largest range of transmission and the best achievable transmission quality. For this reason, it is important to study how a UWB link performs under DAA and to find ways to enable a UWB device to host a DAA

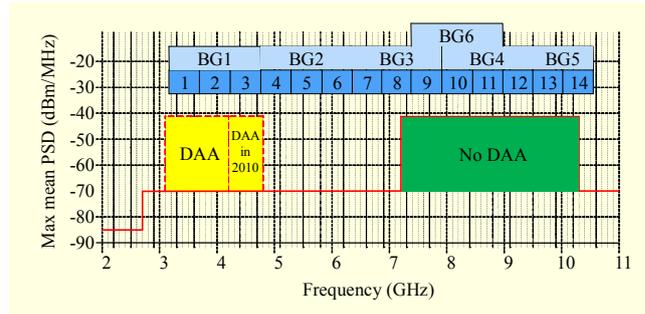


Fig. 1. WiMedia band groups superimposed on the Korean UWB spectrum allocation in Korea.

mechanism more effectively to make full use of the advantages BG offers.

As per the Korean regulation, the application of a DAA mechanism should reduce emitted power to the -70 dBm/MHz level (or completely stop it) within 2 s of detecting a signal stronger than -80 dBm/MHz. This translates to a notch at least $-41.3 + 70 \approx 29$ dB deep in the transmitted spectrum at overlapping bands.

2. WiMedia UWB Standard Overview

The WiMedia UWB standard is supported by a powerful coalition of industry giants such as Intel, Nokia, NEC, Samsung, NXP/Philips, STMicroelectronics, and so on. In addition, it has been chosen for major application technologies, including certified wireless universal serial bus (CW-USB) [7], which will replace the conventional wired USB, and the third generation of Bluetooth (Bluetooth 3.0) [8].

The WiMedia PHY is based on multiband orthogonal frequency division multiplexing (MB-OFDM) technology [9]. In MB-OFDM, the spectrum of 7.5 GHz from 3.1 GHz to 10.6 GHz is divided into 14 bands of 528 MHz each. As elaborated in Fig. 1, the 14 bands form 6 band groups (BGs), where each band group contains 3 bands except for BG5 which contains two. For transmission on one of these band groups, the standard employs a frequency-hopping technique in which the carrier frequency is hopped between the center frequencies of its bands after each OFDM symbol. This is done according to a predefined time-frequency code (TFC). Unique logical channels that can be used simultaneously by multiple UWB piconets are defined by using different TFCs over each band group. The TFC codes for BG1 are listed in Table 1. The TFCs in the other BGs are distributed in the same manner.

A WiMedia transceiver is essentially a conventional OFDM transceiver that uses a total of 128 OFDM subcarriers divided into 100 data subcarriers, 12 pilot subcarriers, 10 guard subcarriers, and 6 unused subcarriers. For low data rates, an MB-OFDM system uses quadrature phase-shift keying

Table 1. Time-frequency coding parameters for BG1.

TFC number	Band ID for TFC						Number of bands employed (λ)
	1	2	3	1	2	3	
1	1	2	3	1	2	3	3
2	1	3	2	1	3	2	3
3	1	1	2	2	3	3	3
4	1	1	3	3	2	2	3
5	1	1	1	1	1	1	1
6	2	2	2	2	2	2	1
7	3	3	3	3	3	3	1
8	1	2	1	2	1	2	2
9	1	3	1	3	1	3	2
10	2	3	2	3	2	3	2

Table 2. DRP time resolutions.

Resolution	Duration	Function
Superframe	65 ms (256 MAS)	Basic timing structure for frame exchange
MAC access slot (MAS)	256 μ s	Slots for data, command, and control frame transmission
Beacon slot (BS)	85 μ s	Allocated for beacon frames transmitted by each device for the purpose of coordination (overlaid on top of MASs)

(QPSK) modulation, whereas for high rates, it uses dual carrier modulation (DCM) [10] to increase diversity at the expense of receiver complexity. DCM introduces additional redundancy by mapping 4 bits onto two 16-point constellations. The symbols from the two 16-point constellations are then mapped onto tones that are separated by at least 200 MHz in bandwidth.

The standard provides a set of four convolutional code rates which are: 1/3, 1/2, 5/8, and 3/4. The last three code rates are generated from the mother rate of 1/3 by employing code puncturing. For improved performance over fading channel conditions, the MB-OFDM standard supports frequency domain spreading (FDS) and time domain spreading (TDS) for low data rates. In FDS, the same data symbol is transmitted twice over two widely separated subcarriers in the same OFDM symbol, whereas in TDS, the same OFDM symbol is transmitted twice on two consecutive time slots.

The minimum interval repetition of all available TFC patterns is every 6 OFDM symbols. Consequently, the standard specifies that the transmitted packet size must be a multiple of 6 OFDM symbols. Thus, the minimum block of coded data we

deal with is a block of coded bits carried on 6 OFDM symbols, which we shall call a *code block* throughout the rest of this paper.

Medium access sharing is provided through a TDMA scheme, which is called a *distributed reservation protocol* (DRP) in the context of the standard. The DRP is based on beaconing, in which beacon packets are transmitted by each device for the purpose of coordination. Each device is able to negotiate its desired time slots with other devices according to service needs. As a result, a UWB device can be aware ahead of time when it can transmit or receive data without any need for time and power consuming channel sensing. Beacons are special packets that carry most of the control information necessary for a distributed network to exist and to be stable. Within the DRP, three time resolutions are defined as shown in Table 2. For every superframe, beacons are transmitted at certain pre-allocated time slots at the beginning of the superframe. A beacon frame contains several information elements (IEs) which carry signaling and control information. For data transmission, each user reserves a certain number of MASs within the DRP protocol according to its service requirements.

The standard supports transmitted spectrum shaping to avoid other narrowband users allocated within the UWB band to comply with DAA requirements. The transmitted signal is sent in the context of a tone nulling (TN) array of 384 elements. These elements correspond to the total number of subcarriers of the band group used for transmission so that TN set {0 to 127} applies to the subcarriers of the lowest frequency band in the current band group, TN set {128 to 255} applies to the middle band, and TN set {256 to 383} applies to the highest band. Each tone nulling element can take the values of 0 or 1. If the value is 0, then the transmitter should take steps to minimize the transmitted signal power at the frequency of the corresponding subcarrier. If the value is 1, then the signal is unaffected by tone nulling. An active device that nulls one or more tones during its transmissions includes a tone nulling IE (TN IE) in its beacon. This makes all other devices in the surrounding range (potential receivers) aware of the shape of the transmitted signal for this device as well as which tones it is going to use in transmitting data.

Since beacons carry very critical information, they are always transmitted over the lowest (and most robust) data rate of 53.3 Mb/s. This data rate employs a convolutional channel coding rate of 1/3 in addition to FDS and TDS. As a result, erroneous reception of beacons is unlikely to occur. The beacon payload is also accompanied by a 4-byte frame check sequence (FCS) to ensure that it is received correctly. If an error is detected, beacon retransmission is requested within an automatic repeat request (ARQ) protocol. Consequently, our

work is based on the fair assumption that the TN array available at the receiver is always free of errors.

II. Detect and Avoid Mechanism

The main requirement for the implementation of a DAA mechanism is to allow peaceful coexistence with other NB systems. DAA is based on the idea that, due to its OFDM-based nature, the WiMedia UWB PHY can be used to perform the two main stages of DAA:

- Spectral analysis of the local environment: The multiband OFDM system already complies with this requirement, since it has the ability to detect interference levels in specific victim receiver bands via the FFT engine.
- Adaptive spectral shaping: By using OFDM, the transmitted spectrum can be easily shaped so as not to inject harmful interference into the victim band.

In the rest of this section, we provide a brief overview of these two stages of the DAA mechanism.

1. Detect Stage

By using the inherent FFT engine in all OFDM transceivers, the MB-OFDM device can act as a spectrum analyzer with a resolution of 4.125 MHz (528 MHz BW/128 points FFT). The average power levels transmitted by other NB devices within the active UWBs can be measured by averaging the received signal over time. Measured power levels for detected links that require an avoid action should exceed a certain threshold that indicates a possible interference hazard. Accurate estimates of detected NB links can be obtained by inserting quiet periods in the network operation, during which all WiMedia devices in the neighborhood start scanning the active bands and then exchange TN IEs through beaconing. This is sometimes called the energy detection approach. However, energy detection suffers a high probability of false alarm (probability of falsely detecting a nonexistent NB link) due to spurs which are usually found in the measured power-spectrum profile [3] due to carrier leakage, I/Q imbalance, and other causes.

Other approaches involve detecting specific features of the targeted NB signal. For example, in the case of WiMax this specific feature could be the packet preamble [11]. This minimizes the probability of false alarm since detection is based on signal type, not energy. However, to be able to detect all kinds of potential NB links would require a library of system features that may vary in different countries, and may need to be updated to include more new systems. This renders such an approach difficult to implement. This is usually called signal type detection or coherent detection.

There is a tradeoff in selecting a method for NB signal

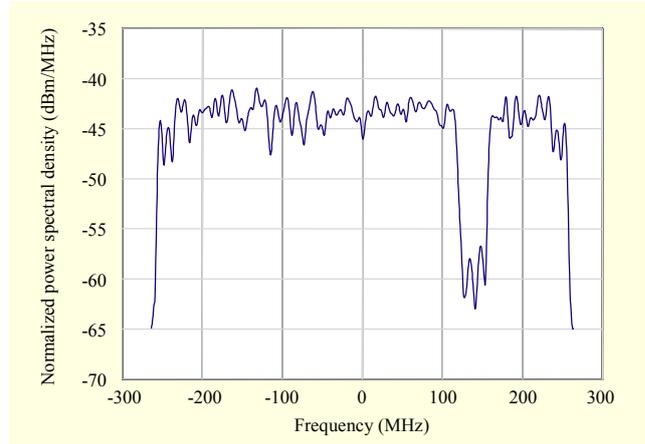


Fig. 2. Transmitted baseband UWB spectrum shape with 10 nulling tones.

detection between simple implementation in energy detection approach, and accuracy in the signal type detection approach. However, the low cost CE type of applications intended for UWB pushes implementers to always adopt the simpler (and cheaper) approach.

2. Avoid Stage

We map the bands occupied by the detected NB links onto the TN array by setting corresponding array elements to 0. The avoid stage acts to protect the narrowband link by ceasing or reducing transmitted power on the overlapping band (the OFDM tones are turned off) to create a notch in the transmitted signal spectrum at this band. This implies that the data carried on the notched portion of the transmit spectrum is spoiled since the signal-to-noise plus interference ratio (SNIR) at victim band will be extremely low.

Figure 2 shows the transmitted baseband spectrum shape in the case of 10 nulling tones. The resulting notch depth is about 15 dB, while at least 29 dB is required. Nulling more tones on both sides of the notch can yield a greater depth; however, in [11] it was shown that even with 40 nulling tones the required notch depth could not be achieved. Various methods have been proposed to increase notch depth, such as active interference cancellation [11] and the application of a digital notch filter in the time domain post-IFFT [3]. However all these methods still entail that data transmitted on these bands will be lost and that the TN array elements corresponding victim tones have to be set to 0 in the TN array.

Redundancy provided by FDS, TDS, and channel coding at low data rates may be exploited to recover lost data. In [3], the target packet error rate (PER) of 8% required by the standard could be reached for low data rates (with lowered link margins). However, for high data rates, the target PER could not be

reached for any transmit power. Hence, the performance of UWB operating in DAA bands is under a high threat, especially for high data rates, which are the most desirable for consumers.

III. Proposed Methodology: Adaptive Data Distribution

In this section, we introduce our methodology for preventing loss of data due to tone nulling. It works to mitigate the negative effects of spectrum shaping on UWB transmission. We call our method the adaptive data distribution (ADD) technique because its main objective is to redistribute data on active tones.

1. Adaptive Data Distribution

Since data transmitted on overlapping bands is usually corrupted due to tone nulling, we adaptively cease transmission of data on these tones and use only the remaining active (not nulled) tones for transmission. This means that the effective bandwidth used for transmission is reduced by a certain ratio. Since adaptive/variable data rate transmission is not supported on the WiMedia MAC, as it implies need for buffering (variable interleaver dimensions and coordination between devices), it is highly desirable to keep the data rate unchanged. Thus, to maintain the data rate at a reduced transmission bandwidth, we have to transmit the original number of information bits per packet within a reduced number of channel coded bits that can be carried on the remaining active tones. In other words, ADD compensates for the reduced number of data-carrying tones by re-adjusting the channel coding rate in a manner that keeps the data rate constant. The possible code rates range from the original code rate used by the current data rate c_0 to the maximum allowable rate c_{\max} . The c_{\max} is specified according to performance requirements.

Table 3 lists all standard data rates with the code rates and spreading they employ. To avoid modifying the standard specifications, we chose c_{\max} to be the maximum code rate available in the standard, which is 3/4. This entails that, according to the table, our work cannot be applied to the data rate of 480 Mb/s, since it already employs the maximum code rate 3/4. However, this can be remedied by adding another puncturing pattern that can generate a larger code rate. This is beyond the scope of this paper, as we are mainly concerned with assessing the integrity of the principle itself and introducing minimum modifications to the standard specifications.

Out of 384 elements of the TN array, we are concerned with the 300 data-carrying tones they include (100 for each band). Since the 3 bands in a BG are not always employed (see

Table 3. Parameters related to PHY data rate.

Data rate (Mb/s)	Spreading (TDS/FDS)	Code rate (c_0)	Info bits per code block	Coded bits per code block
53.3	TDS+FDS	1/3	100	300
80		1/2	150	300
106.7	TDS	1/3	200	600
160		1/2	300	600
200		5/8	375	600
320	None	1/2	600	1,200
400		5/8	750	1,200
480		3/4	900	1,200

Table 1), as it depends on the TFC used. If d tones were required to be nulled, where d might be a combination of tones carrying data, pilots, guards, or unused tones, then the number of data-carrying tones utilized in transmission is

$$\Omega_{\text{Data}} = 100\lambda - \delta, \quad (1)$$

where λ is the number of bands employed in the BG, and δ is the total number of nulled data-carrying tones within d nulled tones in the bands employed. Adopting this methodology, we can determine the minimum number of active (not nulled) data-carrying tones that ADD can handle by

$$\Omega_{\text{Data}}|_{\min} = \left\lfloor 100\lambda \left(\frac{c_0}{c_{\max}} \right) \right\rfloor, \quad (2)$$

where $\lfloor x \rfloor$ stands for the largest integer less than or equal to x .

The probability of nulling a data-carrying tone can be approximated as $P_{\text{Data}}=100/128$, because data carrying tones are almost evenly distributed on the transmission band [5]. Thus, amongst the 384 TN array elements, the minimum number of active tones that ADD can handle is approximately

$$\Omega|_{\min} = \left\lfloor \frac{100\lambda}{P_{\text{Data}}} \left(\frac{c_0}{c_{\max}} \right) \right\rfloor = \left\lfloor 128\lambda \left(\frac{c_0}{c_{\max}} \right) \right\rfloor. \quad (3)$$

This means that a UWB device employing ADD can null from 16% to 55% of its tones, depending on the original code rate employed by the current data rate.

The presence of nulled tones indicates that the bandwidth valid for transmission has been reduced; hence, to maintain the data rate, the number of coded bits for the same number of information bits per code block has to be reduced. For each frame payload, let K be the number of information bits to be transmitted, and let N be the resulting number of coded bits. Hence, the total number of coded bits that can be carried on

Ω_{Data} tones can be calculated as

$$n = \left(\frac{\Omega_{\text{Data}}}{100\lambda} \right) N. \quad (4)$$

To maintain the data rate, we need to encode K bits into n bits only, which yields a required code rate somewhere between two standard data rates (as long as $\Omega_{\text{Data}} \geq \Omega_{\text{Data}}|_{\text{min}}$). Thus,

$$c_x < \left(\frac{K}{n} \right) < c_y, \quad \text{for } \delta > 0, \quad (5)$$

such that

$$\left[c_x, c_y \right] \in \left\{ \frac{1}{3}, \frac{1}{2}, \frac{5}{8}, \frac{3}{4} \right\}. \quad (6)$$

Logically, the required code rate (K/n) for ADD may take rational values with unconventional values, such rates can be achieved by applying very long puncturing patterns over large blocks of coded bits; however, this is a very complex solution due to the long length of the pattern and the very large number of simulations needed to find the optimum patterns required, which tends to be impossible to carry out. We propose a very simple and powerful alternative of applying a hybrid-rate coding scheme, which we explain in next subsection.

2. Hybrid-Rate Coding Scheme

The TN array remains unchanged for at least one superframe, depending on how often NB detection is done; therefore it is guaranteed that no change in the applied TN array takes place within a superframe. Let the K information bits to be transmitted in a frame payload be divided into two subblocks, k_x and k_y , and let them be encoded by standard component code rates c_x and c_y , respectively. Hence,

$$K = k_x + k_y = n_x c_x + n_y c_y, \quad (7)$$

such that

$$n = n_x + n_y. \quad (8)$$

From (7) and (8), we obtain

$$k_x = \frac{c_x c_y}{c_y - c_x} \left(n - \frac{K}{c_y} \right), \quad (9)$$

$$k_y = \frac{c_x c_y}{c_x - c_y} \left(\frac{K}{c_x} - n \right). \quad (10)$$

However, k_x and k_y may not have integer values for all possible number of nulled data tones at all data rates. To fix this, we take the largest possible integer values of k_x and k_y and allow for the insertion of b dummy bits after encoding such that exactly n encoded bits result from the whole process. Dummy

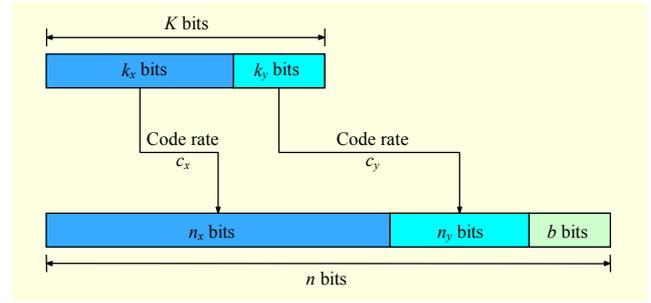


Fig. 3. HR coding scheme.

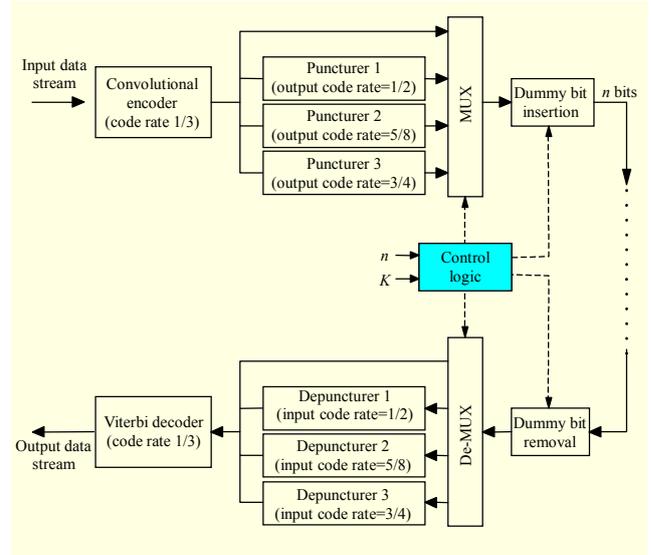


Fig. 4. Hybrid-rate encoding and decoding at transmitter and receiver.

bits are then removed before decoding at the receiver. As a result, we replace the term n by $(n-b)$ in (7) to (10). Our calculations show that the term b shall not exceed 3 bits in any case. Figure 3 shows a schematic diagram that further elaborates the HR coding scheme for convenience. Decoding is exactly the opposite of the encoding process. The receiver uses the TN IE it received through beaconing to extract all the required parameters used in the encoding process.

As previously mentioned, standard code rates are all generated from a single mother convolutional encoder with rate 1/3 by application of different puncturing patterns. HR coding operates by multiplexing through the outputs of puncturers according to the calculated values of k_x and k_y . The channel encoding and decoding processes within the WiMedia transmitter/receiver are described in Fig. 4.

HR coding can be considered a linear combination between its two component code rates. Assuming the number of coded bits per coded block is large enough and they are well interleaved to distribute error events uniformly over subblocks, the overall probability of bit error can be written as

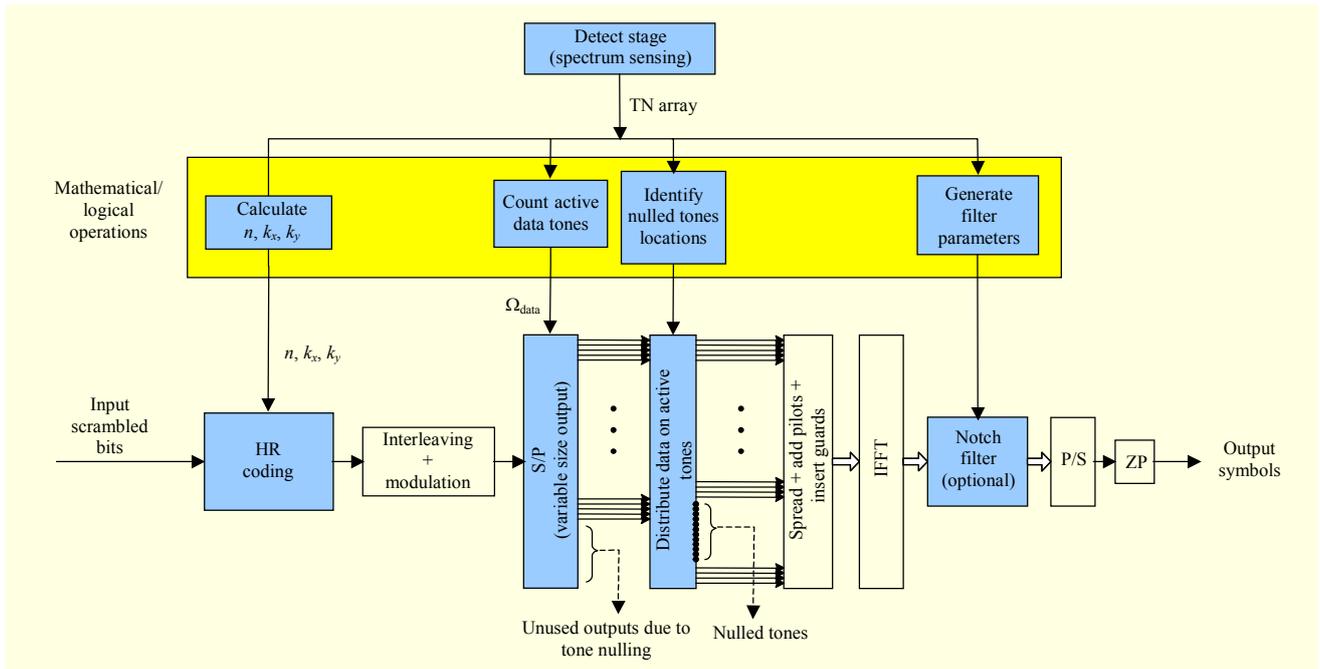


Fig. 5. Block diagram of the OFDM-based transmitter architecture extended to support ADD. Blue blocks represent those involved in DAA/ADD.

$$P_b = \frac{P_{\text{Data}}}{K} (k_x P_x + k_y P_y), \quad (11)$$

where P_{Data} is the probability of a nulled tone being a data-carrying tone equal to $(100/128)$, and P_x and P_y are the bit error probabilities corresponding to code rates c_x and c_y , respectively. Equation (11) indicates that the performance of any code rate between c_x and c_y is lower bounded by the performance of code rate c_x and upper bounded by the performance of code rate c_y .

A block diagram representing the overall design and operation of the UWB transmitter employing DAA with ADD is shown in Fig. 5. Blocks in blue represent those related to DAA/ADD operation. The notch filter is added to increase the notch depth; however, it is optional and can be replaced by any other technique to increase the notch depth. In the figure, we can see that, other than HR coding, ADD does not impose any major modification to the standard PHY architecture. It only changes the way data is distributed for OFDM tones.

IV. Results and Discussion

In this section, we present our simulated results to investigate the UWB link performance under the DAA mechanism, which gives us insight into how efficiently UWB devices can perform in the DAA-required band in Korea and in other countries requiring DAA. We also show how our proposed methodology can provide better support of DAA by mitigating the negative

effects resulting from spectrum shaping.

1. Simulation Environment and Assumptions

We built a baseband-equivalent SIMULINK® model on MATLAB®, according to the WiMedia ECMA-368 standard specifications [5]. Simulations were done over a UWB channel as described in [13]. Four separate channel models (CM1-CM4) are available for UWB system modeling, each with arrival rates and decay factors chosen to match a different usage scenario [14]. The four models are the following:

- CM1: 0 m to 4 m line-of-sight (LOS),
- CM2: 0 m to 4 m non-LOS,
- CM3: 4 m to 10 m non-LOS,
- CM4: extreme non-LOS multipath channel.

We selected the CM2 model for our simulations, since we target high data rates, which naturally can only be achieved at short ranges (0 m to 4 m). Also, this model complies with the non-LOS nature of most indoor environments intended for UWB operation. The model is provided with 100 channel realizations which can be found in [14]. Results shown represent the average of the best 5 channel realizations among 20 randomly-selected channel realizations.

Simulations were carried out for the 200 Mb/s data rate with the coding and spreading parameters listed in Table 3. The model employs the full multiband mode (3-band hopping pattern with $\lambda=3$) unless otherwise mentioned. All PER curves were obtained by averaging PER values over all possible notch locations. We

also assumed that the receiver is aware of the TN IE employed by the transmitter in all cases. This is a realistic assumption since TN IE is included within beacons that are transmitted using the most robust data rate as explained in section I.2.

Finally, our simulations do not incorporate implementation related losses such as clipping at the DAC, ADC degradation, clock frequency mismatch, carrier offset recovery, and so on. Nevertheless, they incorporate losses due to front-end filtering and channel estimation errors including those due to pilot tone nulling.

2. Performance under Various Notch Widths

Figure 6 demonstrates the effect of increased notch width on link performance. It shows PER curves for $d=20$ and $d=40$ nulled tones with notch widths of 82.5 and 165 out of 1,584 MHz. This effect is investigated in two cases: ADD applied and ADD not applied.

When ADD is not applied, the average slope of the PER curves decreases as the notch width increases, which implies the following. First, the target 8% PER may not be reached at a reasonable value of SNR for large number of nulled tones. This can be seen clearly in the figure for $d=40$. Second, for large notch widths, increased SNR does not yield a significant improvement in performance. Moreover, PER may reach a phase of saturation at a certain stage. This is because, even though the SNR is increased, the data carried on nulled tones is still corrupted due to the applied notch, which sets an upper-bound on performance which cannot be crossed.

When ADD is applied, the average slope of the PER curves is almost the same as that of the “no notch” curve, since nulled tones are not used at all for transmission. According to (11), HR coding theoretically should follow the slope of its standard component code rates. Degradation introduced by ADD is referred to the increase in code rate it implies.

3. Performance under Various TFCs

Figure 7 elaborates another critical issue, which is how different TFC patterns perform under DAA. The figure compares link performance with 12 tones nulled in the case of frequency hopping between 3 bands ($\lambda=3$, full multibanding mode) to the case of only 1 band used for transmission ($\lambda=1$, FDMA mode). Full multibanding outperforms the FDMA mode by about 5 dB. This can be explained by the following reasons. First, $d=12$ nulled tones represent only 3% of the total bandwidth (12 out of 384) in the full multibanding mode. However, in the FDMA mode, 12 tones represent about 10% (12 out of 128) of the total bandwidth. Second, time domain spreading does not give a significant advantage in the FDMA mode because the spread OFDM symbol is sent twice over the

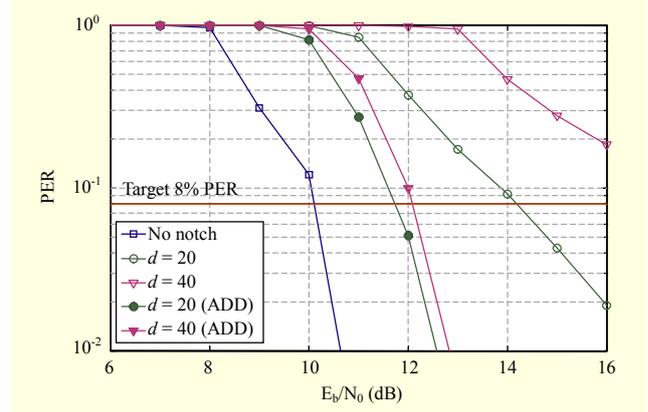


Fig. 6. PER curves for 20 and 40 notched tones, comparing performance without ADD to that with ADD applied.

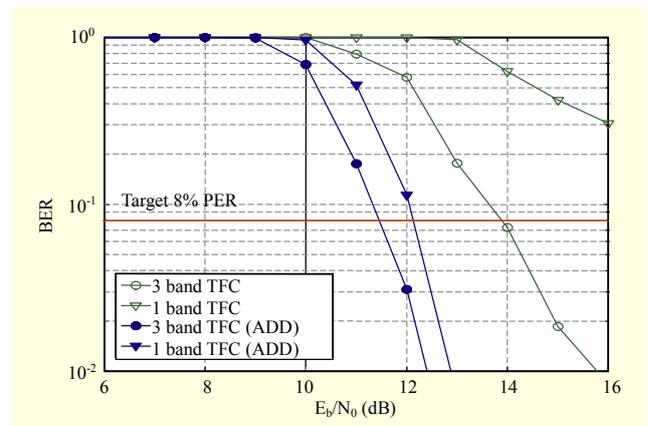


Fig. 7. PER curves for 1 and 3 band TFCs for 12 notched tones comparing performance without ADD to that with ADD applied.

same band and the same notch location; hence, the diversity advantage provided by TDS is minimized. Thus, FDMA mode has far less chance of satisfying performance requirements if it operates under conventional DAA. On the other hand, upon applying ADD, very small deterioration in performance is noticed in the FDMA mode compared to full multibanding due to the first reason. In addition, ADD allows the FDMA mode to make full use of the diversity advantage provided by TDS, which further enhances performance.

V. Conclusion

In this paper, we investigated the current UWB regulations in Korea, and highlighted the regulations regarding interference mitigation at certain bands. We introduced the DAA mechanism, which was selected by regulators to realize the interference mitigation requirement in these bands. As we clarified that employing DAA implies significant performance degradation upon data transmission, we proposed a simple but

practical methodology that can enable UWB devices to support DAA more efficiently and mitigate its effects on UWB link performance without affecting the data rate. Our methodology incorporates a novel channel coding scheme that enables UWB PHY to achieve very high flexibility in channel coding rates. Our work can be integrated in the WiMedia UWB PHY without requiring major modifications, and it does not add any significant complexity to operation. Therefore, it complies with the spirit of low cost consumer electronics applications intended for UWB. Furthermore, it operates with full transparency to upper layers because the whole operation can be run and controlled within the PHY. For these reasons, it may represent an attractive option. Simulated results showed that our proposed methodology can improve performance significantly over various possible DAA scenarios. Consequently, adopting our methodology can provide more robust UWB operation in Korea and other countries.

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