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Hybrid ARQ with Rate Adaptation in Multiband OFDM UWB Systems

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***Abstract*— In this paper, we propose a cross-layer design (CLD) scheme combining rate adaptation and four types of hybrid automatic repeat request (HARQ) for multiband orthogonal frequency division multiplexing (MB-OFDM) ultra wideband (UWB) systems following the ECMA-368 standard. The time varying property is incorporated into standard UWB channel models for the purpose of investigating rate adaptation. To accurately accommodate fast time-varying channel conditions, we propose to embed the selected rate information into the acknowledgement (ACK) frames. It is shown that the proposed CLD scheme combining rate adaptation and HARQ can provide higher throughput than the HARQ-only schemes. Among the four types of HARQ schemes, HARQ Type-III has the best throughput performance while Type I has the worst.**

I. Introduction

UWB technology has been demonstrated as a promising solution for high-rate, low-power, and short-range wireless personal area networks (PANs). A PAN can connect several devices in the short range up to 10 meters in an ad hoc manner. WiMedia aims to promote wireless multimedia connectivity and interoperability between devices in a PAN. In the recent ECMA-368 standard [1], WiMedia specified a physical (PHY) layer based on MB-OFDM UWB techniques and a fully decentralized medium access control (MAC) layer for the communication in a PAN.

Compared with non-adaptive schemes, rate adaptation can significantly improve the throughput efficiency by adapting the system transmission rate to time-varying channel conditions. This can be done by, e.g., adaptive modulation and coding (AMC) techniques [2]. Although the PHY/MAC layer of the ECMA-368 standard did provide the function of the rate adaptation, it did not specify how to implement this function. Traditional AMC techniques in OFDM systems were based on bit loading and power allocation on each subcarrier [3]. However, they are not suitable for MB-OFDM UWB systems, where the same modulation scheme is employed for all the subcarriers. There are only a few papers, such as [4] and [5], investigating the AMC technique for UWB systems. However, how to implement rate adaption for MB-OFDM UWB systems following the ECMA-368 standard is still an open problem.

In the ECMA standard, the ACK policies only specified the methods of exchanging error control messages but how to realize error control was not mentioned. HARQ possesses the merits of both the forward error control and ARQ and can achieve a good tradeoff in both the communication efficiency and reliability. Therefore, HARQ is a good candidate for the standard. In the literature, there are four types of HARQ schemes, namely, HARQ Type-I [6], Type-II with Chase combining (CC) [7], Type-II with incremental redundancy (IR) [8], and Type-III [9]. These four types of HARQ schemes have been applied to many wireless systems, such as WCDMA [10] and IEEE 802.11a [11]. In [12], the performance of MB-OFDM UWB systems employing HARQ Type-I and Type-III schemes was studied. However, the performance of MB-OFDM UWB systems with HARQ Type-II IR and Type-II CC schemes has not been investigated.

Nowadays, CLD is often considered by combining the AMC at the physical layer and HARQ at the data link layer, instead of studying them separately. The research so far, however, has only focused on the combination of HARQ Type-I or Type-II CC scheme with AMC, e.g., [8], [13]. The performance of HARQ Type-III in the CLD has not yet been researched. Also, no performance comparison has been done regarding four types of HARQ schemes combining the AMC in the CLD. The aim of this paper is to fill the above gaps. We propose to combine rate adaptation with various HARQ schemes to improve the throughput efficiency of MB-OFDM UWB systems. Furthermore, a method of implementing the rate adaptation function by incorporating the selected rate information into the ACK frames is proposed in order to catch the time variance of the channel.

The rest of the paper is organized as follows. In Section II, the PHY and MAC layers defined in the ECMA-368 standard are briefly reviewed. How to model the time varying UWB channels, which is essential for the simulations of the rate adaptation function, is described in Section III. In Section IV, the proposed CLD combining various HARQ schemes with rate adaptation is explained. Simulation results are discussed in Section V. Finally, the conclusions are drawn in Section VI.

II. The MB-OFDM UWB System

A. The ECMA-368 PHY Layer Specifications

In the underlying MB-OFDM UWB system, the overall 7.5 GHz (3.1–10.6 GHz) bandwidth is divided into 14 bands, each having a bandwidth of 528 MHz and 128 subcarriers. The

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center frequency of each OFDM symbol is hopped according to the predefined time-frequency codes (TFCs). As shown in Fig. 1, the transmitter side of the system includes a convolutional encoder, interleaver, modulator, OFDM transmitter, and frequency hopper, while the receiver side includes correspondingly a frequency dehopper, OFDM receiver, demodulator, deinterleaver, and Viterbi decoder. The system supports 8 data rates (see Table I) with different coding, modulation, and spreading techniques [1]. Various code rates are derived from a rate 1/3 mother convolutional code by puncturing. After encoding, the interleaving is performed to provide the robustness against burst errors within each 6 consecutive OFDM symbols, which are also the minimum data transmission units. QPSK modulation and dual-carrier modulation (DCM) are employed for data rates of 200 Mb/s or lower and 320 Mb/s or higher, respectively. For data rates of 200 Mb/s and below, the time domain spreading technique is employed by sending the same OFDM symbol twice in a row. For the data rates of 53.3 Mb/s and 80 Mb/s, frequency domain spreading technique is further employed by transmitting the same information on two separate subcarriers within the same OFDM symbol to improve the frequency diversity. The supported data rates, modulation modes, coding rates and information bits per 6 OFDM symbols are listed in Table I.

In the ECMA-368 standard, the PHY layer consists of two sublayers, i.e., the PHY layer convergence protocol (PLCP) sublayer and the physical medium dependent (PMD) sublayer. The PLCP sublayer defines a method of mapping the PLCP service data unit (PSDU) into the PLCP packet data unit (PPDU). The PPDU consists of the PLCP preamble, PLCP header, and PSDU. Two kinds of PLCP preambles are defined, namely, the burst preamble and standard preamble, which consist of 18 and 30 OFDM symbols, respectively. Both PHY and MAC layer headers are included in the PLCP header, which has a fixed length of 12 OFDM symbols. The PSDU contains the payload (up to 4095 bytes), frame check sequence (FCS) of 4 bytes, 6 tail bits, and pad bits, the purpose of which is to ensure that the resulting length of the PSDU is the multiple integers of 6 OFDM symbols due to the interleaving operation. Let us define N_{pre} as the number of OFDM symbols in the PLCP preamble, L_P as the payload size in bytes, N_I as the number of information bits carried per 6 OFDM symbols, and T_{sym} as an OFDM symbol duration, which equals 312.5 ns in the standard. The time duration T_P of transmitting a PPDU can then be calculated as

$$T_P = T_{\text{sym}}(N_{\text{pre}} + 12 + 6\left\lceil\frac{8L_P + 38}{N_I}\right\rceil) \quad (1)$$

where $\lceil x \rceil$ denotes the smallest integer not less than x.

B. The ECMA-368 MAC Layer Specifications

The MAC layer is based on a synchronized and totally distributed solution. Two channel access methods, namely, the distributed reservation protocol (DRP) and prioritized channel access (PCA), were specified in the standard.

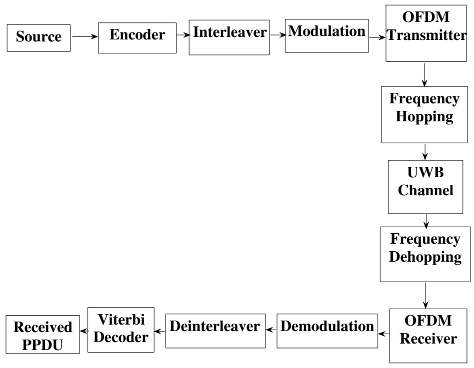

Fig. 1. The block diagram of the MB-OFDM UWB system.

Table I. Available data rates and relevant parameters.

Data Rate (Mb/s)	Modulation	Code Rate	Information Bits Per 6 OFDM Symbols (N_I)
53.3	QPSK	1/3	100
80	QPSK	1/2	150
106.7	QPSK	1/3	200
160	QPSK	1/2	300
200	QPSK	5/8	375
320	DCM	1/2	600
400	DCM	5/8	750
480	DCM	3/4	900

The basic timing structure for the frame exchange of the MAC layer is a fixed length superframe, composed of 256 medium access slots (MASs). Each MAS is 256 μs. A superframe is therefore 65.536 ms and it starts with a beacon period (BP) followed by a data transfer period (DTP). Transmission opportunity (TXOP) is a time interval, with the limit $T_{TXOPLimit}$, obtained by a device using either the PCA or DRP to initiate transmissions.

The ECMA-368 standard also defines three ACK policies, i.e., No-ACK, immediate ACK (Imm-ACK), and block ACK (B-ACK). No ACK frame is generated when the device receives a frame with the No-ACK policy. On the reception of a frame with the Imm-ACK policy, a device shall respond with an Imm-ACK frame to the transmitter after the short interframe space period, $pSIFS$ = 10μs. Also, another $pSIFS$ is needed between the Imm-ACK frame and the up-coming frame. The B-ACK policy allows a source device to transmit multiple frames and receive a single ACK frame from the receiver indicating which frames are received and which frames need to be retransmitted.

III. Time Varying UWB Channel Models

A. IEEE 802.15.3a UWB Channel Models

Channel models for UWB have been standardized by the IEEE 802.15.3a [14]. They model multipath components in clusters. Each cluster and each ray within each cluster are assumed to experience independent fading. Multipath gain coefficients follow a log-normal distribution. Poisson processes are used to model cluster and ray arrival rates, while a negative exponential distribution describes the power delay profile.

Four different scenarios are defined based on various measurement environments, namely channel models 1–4 (CM1–CM4) [14]. CM1 describes a line-of-sight (LOS) scenario with a distance range less than 4 m. CM2 describes a non-LOS situation within the same range of CM1. CM3 describes a larger distance range 4–10 m for a non-LOS scenario, while CM4 describes an "extreme non-LOS multipath situation".

B. Time Variance in UWB Channels

In most applications of MB-OFDM UWB systems, the mobility of the terminal is limited to the pedestrian speed or slower. Thus, the time variation characteristics are not included in IEEE 802.15.3a channel models. However, to study the rate adaptation, modeling the time variance of UWB channels is very important since the system needs to adapt the transmission rate based on time-varying channel conditions.

In [15], it was suggested that the time variance can be added to the UWB channel models in terms of the approximate angular power spectrum depending on the delay of each path. If the time variance is due to the movement of the transmitter and/or receiver, we can model the UWB channel by the following time varying impulse response [16]

$$h(t,\tau) = X \cdot \Sigma_{l=0}^{L-1} \Sigma_{k=0}^{K_l-1} \xi_l \beta_{k,l} g_{k,l}(t) \delta(\tau - T_l - \tau_{k,l}) \quad (2)$$

where L is the number of clusters and K_l is the number of rays within the l-th cluster; T_l is the l-th cluster delay and $\tau_{k,l}$ is the delay of the k-th ray within the l-th cluster relative to the lth cluster arrival time T_l; X represents the log-normal shadowing; ξ_l and $\beta_{k,l}$ are the cluster fading and the ray fading, respectively, each following an independent log-normal distribution. The time-varying gains $g_{k,l}(t)$ are independent Gaussian stationary processes with zero mean and unit power. Their angular power spectrum depends on the delay τ of the k-th ray within the l-th cluster and can be expressed as

$$pdf(\alpha,\tau) = \left\{ \begin{array}{ll} \frac{1}{4\arcsin(\frac{\tau}{\bar{\tau}})}, & \tau < \bar{\tau} \\ \frac{1}{2\pi}, & \tau \geq \bar{\tau} \end{array} \right\} \quad (3)$$

where $\bar{\tau}$ is the delay threshold, which ensures the total r.m.s angular spread is 38 degrees, and α is the arriving angle.

From the angular power spectrum, we can obtain the corresponding Doppler spectrum [15]. The Doppler spread f_{ds} of the above time-varying gains can then be computed as

1) for $\tau \geq \bar{\tau}$

$$f_{ds} = \int_{-f_{\text{max}}}^{f_{\text{max}}} \frac{1}{\pi} \frac{f^2}{\sqrt{f_{\text{max}}^2 - f^2}} df = f_{\text{max}}^2/2 \quad (4)$$

2) for $\tau < \bar{\tau}$

$$\begin{aligned} f_{ds} &= \int_{\frac{\tau}{\bar{\tau}} f_{\text{max}}}^{\frac{\tau}{\bar{\tau}} f_{\text{max}}} \frac{1}{2\arcsin(\frac{\tau}{\bar{\tau}})} \frac{f^2}{\sqrt{f_{\text{max}}^2 - f^2}} df \\ &= \frac{f_{\text{max}}^2}{2}(1 - \frac{\sin(2\arcsin(\frac{\tau}{\bar{\tau}}))}{2\arcsin(\frac{\tau}{\bar{\tau}})}), \quad (5) \end{aligned}$$

where f_{max} is the maximum Doppler frequency. Since the coherence time of a channel is approximately $1/f_{ds}$, the minimum coherence time here is about $2/f_{\text{max}}^2$.

IV. HARQ with Rate Adaptation in MB-OFDM UWB Systems

In this paper, we consider the file transfer application in a point to point PAN. This application is not sensitive to the delay and prefers the maximum throughput. Since there are only two devices in this small PAN, the DRP with the Imm-ACK policy is adopted for the transmission.

A. Rate Adaptation

In the ECMA-368 standard, the rate adaptation function is supported by using Link Feedback Information Element (IE) to notify each other for the preferred data rate. The most common way to transmit this IE is in beacons. Here, we assume that the terminal has the normal walking speed of v=1 m/s. TFC1 is selected as the frequency hopping sequence. From $f_{\text{max}} = f_c v/c$, where c is the speed of light and f_c is the carrier frequency, we can obtain f_{max}=13.2 Hz. The corresponding minimum coherence time is approximately 11.5 ms. This means that the channel changes significantly during one superframe, with the duration of 65.536 ms. Therefore, an update of the data rate for every superframe may not accommodate fast channel variations. A better way is to transmit the recommended data rate in an ACK frame. ACK frames are sent after a certain amount of packets, which has a smaller duration than a superframe. In this manner, the system can adapt better to the time-varying channel conditions without changing the standard significantly.

One of the challenges in the rate adaptation implementation is how to select the data rate mode. Conventionally, the data rate is determined based on the estimated signal-to-noise ratio (SNR) at the receiver. Then, a bunch of SNR switching points are obtained either heuristically or through some empirical formulas of packet error rate (PER) versus SNR. In this paper, we will rely on the following approximate PER to simplify the rate adaptation design [8], [13]

$$PER_{m,n}(\gamma) \approx \left\{ \begin{array}{lll} 1, & \text{if} & 0 < \gamma < \gamma_{m,n} \\ a_{m,n} e^{-g_{m,n}\gamma}, & \text{if} & \gamma \geq \gamma_{m,n} \end{array} \right. \quad (6)$$

where m is the type of the ARQ scheme, n is the index of the data rate mode, $a_{m,n}$ and $g_{m,n}$ are rate-dependent coefficients, $\gamma_{m,n}$ represent rate-dependent SNR switching points, and γ is the average received SNR. In order to fulfill the QoS requirement, the overall transmission PER should be smaller than a target PER P_{target}. According to (6), the SNR switching points $\gamma_{m,n}$ are obtained as

$$\gamma_{m,n} = \frac{1}{g_{m,n}} ln(\frac{a_{m,n}}{P_{\text{target}}}). \quad (7)$$

After some calculations, the rate dependent parameters $a_{m,n}$, $g_{m,n}$, and $\gamma_{m,n}$ were obtained and shown in Table II. Note that the parameters of the lowest data rate of 53.3 Mb/s are not included due to the assmption of lossless transmissions in the SNR range of 0–18 dB.

In the DRP with Imm-ACK scenario, the effective throughput (ET) can be calculated as

$$ET = \frac{8N_e L_P}{T_{DRP}} \quad (8)$$

where N_e is the effective number of PPDUs that can be transmitted in one TXOP, T_{DRP} is the actual time required to successfully deliver those PPDUs in one TXOP, which is equal to the duration of a superframe. We can calculate N_e as

$$N_e = \left\lfloor \frac{T_{TXOPLimit}}{T_P + T_{ImmACK} + 2pSIFS} \right\rfloor PER_{m,n}(\gamma)\,, \qquad (9)$$

where $\lfloor x \rfloor$ denotes the largest integer not greater than x. Since we consider only two users, the length of BP will be 2 MASs and the duration of DTP will be 254 MASs, which equals $T_{TXOPLimit}$. In the standard, the Imm-ACK frame does not have any payload. Here, the Imm-ACK frame is used for indicating the recommended data rate to the transmitter. So the payload length will be the minimum length of payload, i.e., 1 byte. If we assume the Imm-ACK frame is error free and use data rate of 53.3 Mb/s, the duration T_{ImmACK} of an Imm-ACK frame is 15 μs according to (1).

B. HARQ

HARQ Type-I scheme [6] has constant error correction capability in each transmission. There is no difference between transmitted and retransmitted frames. For HARQ Type-II CC scheme [7], the retransmitted frame is the same as the first transmitted frame. The soft bits probability information of the transmitted and retransmitted frames are combined in the receiver for decoding. The combining operation requires buffers in the decoder to store the soft bits probability information. These two HARQ schemes can be easily applied to MB-OFDM UWB systems with minor changes in the decoder.

For HARQ Type-II IR and Type-III schemes, the puncture matrices for each transmission should be carefully selected in order to keep the retransmission have the same length as the first transmission due to the interleaver restriction. In HARQ Type-III scheme, a retransmitted packet uses the puncture matrix which is complementary with the puncture matrix of the first transmission. This so-called complementary puncture matrix is obtained by simply shifting the puncture matrix of the first transmission to the left or right. In HARQ Type-II IR scheme, retransmissions typically carry additional redundant information, which is combined with the previously received packets and results in a lower code rate. In Table III, we show the obtained puncture matrices for different code rates and transmissions in HARQ Type-II IR and Type-III schemes.

V. Simulation Results and Discussions

We adopt the IEEE 802.15.3a CM2 with time variance. The rate adaptation function is implemented in the rate controller at the receiver. The data rate is selected according to the average received SNR. For simplicity, the perfect SNR knowledge is assumed to be available at the receiver. The CCITT CRC-32 is employed as the generation polynomial of the FCS, which is assumed to be error-free. We use L_P=50 bytes. The maximum number of transmissions is defined as 4, while $P_{\text{target}} = 10^{-4}$.

Fig. 2 shows the ETs of the MB-OFDM UWB system with HARQ Type-I scheme only (without rate adaptation) for different data rates and with the combination of HARQ Type-I and rate adaptation. It is clearly shown that the CLD scheme combining HARQ and rate adaption outperforms the HARQ-only (non-adaptive) scheme for all the received average SNRs in terms of the throughput.

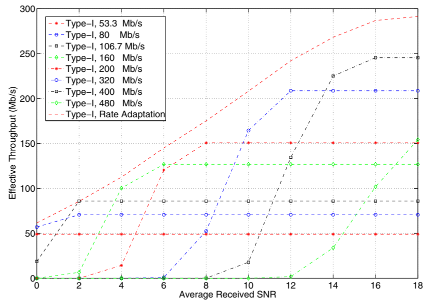

Fig. 2. Effective throughputs of the MB-OFDM UWB system with HARQ Type-I only (without rate adaptation) and with the combination of HARQ Type-I and rate adaptation.

Fig. 3 shows the ETs of the MB-OFDM UWB system with the combination of rate adaptation and four types of HARQ schemes. It is demonstrated that HARQ Type-II IR and Type-III schemes outperform HARQ type-II CC and Type-I schemes in terms of the throughput. This is due to the fact that HARQ Type-II IR and Type-III schemes decrease the code rate through transmitting only the punctured bits during retransmissions, which increases the probability of successful decoding. HARQ Type-III Scheme is slightly superior to HARQ Type-II IR concerning the throughput performance. HARQ Type-I scheme is the worst among the four different HARQ schemes in terms of the ET.

VI. Conclusions

In this paper, we have proposed a CLD scheme combining rate adaptation with four types of HARQ for MB-OFDM UWB systems based on the ECMA-368 standard. To catch the time-variance of UWB channels, the rate adaptation function has been implemented by incorporating the chosen rate information into the ACK frame. We have thoroughly investigated the ETs of the MB-OFDM UWB system with HARQ scheme only (without rate adaptation) and with the combination of HARQ and rate adaptation. Numerical results show that the proposed CLD scheme has better throughput performance than layer-independent schemes (HARQ-only, without rate adaptation). For the combination of rate adaptation and HARQ schemes, HARQ Type-III scheme can achieve the highest throughput, but it is the most complex one. HARQ Type-I has the worst throughput performance, but it has the lowest complexity. HARQ Type-II CC is a good compromise in terms of the ET and design complexity.

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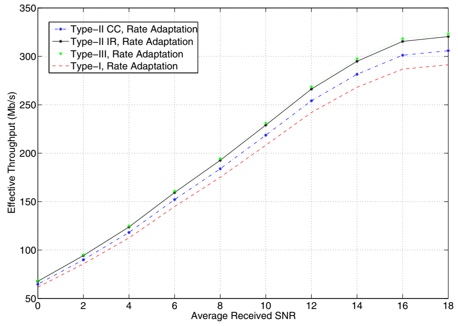

Fig. 3. Effective throughputs of the MB-OFDM UWB system with the combination of rate adaptation and four types of HARQ schemes.

REFERENCES

[1] ECMA-368, "High rate ultra wideband PHY and MAC standard," Dec. 2005, http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-368.pdf.

[2] A. J. Goldsmith and S. G. Chua, "Adaptive coded modulation for fading channels," *IEEE Trans. Commun.*, vol. 46, no. 5, pp. 595–602, May 1998.

[3] A. M. Wyglinski, P. Kabal, and F. Labeau, "Adaptive bit and power allocation for indoor wireless multicarrier systems," *Proc. Int. Conf. on Wireless Communications,* Calgary, Canada, Jul. 2003, pp. 500–508.

[4] Z. Cao and J. W. Mwangoka, "Adaptive modulated MIMO-OFDM for ultra wideband channel," *Proc. IEEE MAPE 2005,* Beijing, China, Aug. 2005, pp. 1037–1040.

[5] N. J. August, R. Thirugnanam and Dong Sam Ha, "An adaptive UWB modulation scheme for optimization of energy, BER, and data rate", *Proc. Joint UWBST & IWUWBS 2004,* Kyoto, Japan, May 2004, pp. 182–186.

[6] S. Lin and P. S. Yu, "A hybrid ARQ scheme with parity retransmission for error control of satellite channels," *IEEE Trans. Commun.,* vol. 30, no. 7, pp. 1701–1719, July 1982.

[7] D. Chase, "Code combining—A maximum-likelihood decoding approach for combining an arbitrary number of noisy packets," *IEEE Trans. Commun.,* vol. 33, no. 5, pp. 385–393, May 1985.

[8] Y. Zhang, D. Yuan, and C.-X. Wang, "Cross-layer design based on RC-LDPC codes in MIMO channels with estimation errors," *International Journal of Electronics and Communications, AEUE,* vol. 62, no. 9, pp. 659–665, Oct. 2008.

[9] S. Kallel, "Complementary puncture convolutional codes (CPC) and their applications," *IEEE Trans. Commun.,* vol. 43, no. 6, pp. 2005–2009, Jun. 1995.

[10] E. Malkamaki, D. Mathew, and S. Hamalainen, "Performance of hybrid ARQ techniques for WCDMA high data rates," *Proc. VTC-Spring 2001,* Rhodes, Greece, May 2001, pp. 2720–2724.

[11] E. C. Strinati, S. Simoens, and J. Boutros, "Performance evaluation of some hybrid ARQ schemes in IEEE 802.11a networks," *Proc. VTC-Spring 2003,* Seoul, Korea, Apr. 2003, pp. 2735–2739.

[12] D. Lowe and X. Huang, "Hybrid automatic repeat request for MB-OFDM ultra-wideband," *Proc. ICWMC 2007,* Guadeloupe, France, Mar. 2007, pp. 13.

[13] Q. Liu, S. Zhou and G. B. Giannakis, "Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1746–1755, Sept. 2004.

[14] J. Foerser, "Channel modeling sub-committee report final," *IEEE P802.15-02/368r5-SG3a*, Dec. 2002.

[15] S. V. Schell, "Analysis of time variance of a UWB propagation channel", *IEEE P802.15-02/452-SG3a*, Nov. 2002.

[16] N. Laurenti and P. Toniolo, "Performance of the multi-band OFDM UWB system with time-varying channels," *Proc. WPMC 2004,* Abano Terme, Italy, Sept. 2004.

Table II. Rate-dependent parameters for the PER fitting.

$a_{m,n}$	80 Mb/s	106.7 Mb/s	160 Mb/s	200 Mb/s	320 Mb/s	400 Mb/s	480 Mb/s
HARQ Type-I	0.022	0.116	168.05	99.4	50.6	44.8	35.5
HARQ Type-II CC	0.021	0.115	162.2	98.5	48.6	43.6	33.4
HARQ Type-II IR	0.02	0.113	160.7	95.2	47.2	42.3	30.1
HARQ Type-III	0.02	0.113	159.8	95.2	46.9	41.8	30.9
$g_{m,n}$	80 Mb/s	106.7 Mb/s	160 Mb/s	200 Mb/s	320 Mb/s	400 Mb/s	480 Mb/s
HARQ Type-I	2.1891	1.8597	6.5891	4.8974	2.6883	1.8953	0.3768
HARQ Type-II CC	2.268	1.8976	6.5289	4.8974	2.6645	1.8953	0.3625
HARQ Type-II IR	2.351	1.9549	6.5067	4.8974	2.3756	1.8953	0.3508
HARQ Type-III	2.371	1.9709	6.5012	4.8974	2.2748	1.8953	0.3487
$\gamma_{m,n}$ (dB)	80 Mb/s	106.7 Mb/s	160 Mb/s	200 Mb/s	320 Mb/s	400 Mb/s	480 Mb/s
HARQ Type-I	-0.512	-0.056	1.07	3.09	5.8	9.8	12.8
HARQ Type-II CC	-0.533	-0.078	1.07	3.08	5.7	9.2	12.7
HARQ Type-II IR	-0.536	-0.097	1.38	3.3	5.6	9.3	12.6
HARQ Type-III	-0.536	-0.089	1.5	3.5	5.6	9.5	12.6

Table III. Puncture matrices of each transmission for HARQ Type-II IR and Type-III schemes.

HARQ Types	Type-II IR	Type-II IR	Type-II IR	Type-III	Type-III	Type-III
code rate	1/2	5/8	3/4	1/2	5/8	3/4
1st transmission	[101]	10101 10101 01010	100 100 011	[101]	10101 10101 01010	100 100 011
2nd transmission	[011]	01110 01010 10101	011 011 000	[011]	01011 01011 10100	001 001 110
3rd transmission	[101]	10101 10101 01010	100 100 011	[110]	10110 10110 01001	010 010 101
4th transmission	[110]	01110 01010 10101	011 011 000	[101]	01101 01101 10010	100 100 011