Cyber Journals: Multidisciplinary Journals in Science and Technology, Journal of Selected Areas in Telecommunications (JSAT), July Edition, 2013
Volume 3, Issue 7

Toward a High Capacity of 60-GHz Ultra-WideBand Radio over Fiber System Based on SCM/DWDM

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***Abstract*— A 60-GHz Ultra-WideBand (UWB) Radio over Fiber (UWBoF) System employing Subcarrier Multiplexing/Dense Wavelength Division Multiplexing (SCM/DWDM) is firstly proposed to improve high channel efficiency for high-capacity UWB communication systems. SCM/DWDM is first utilized to the UWBoF system, due to the better channel efficiency with narrower channel spacing of the DWDM and the unique commonality of the simple SCM, achieving an aggregate bit rate 30 Gbps and high-mobility requirements for the 60 GHz microcell. The novel Optical Frequency Multiplication (OFM) Modulation (Frequency Quadrupler) of 15 GHz lower RF is more cost-effective with much lower RF requirement and dispersion-tolerant even up to a 50 km optical transmission distance in the standard Single-Mode Fiber (SMF), compared with Optical Double-Sideband (DSB) Modulation of 30 GHz higher RF. Moreover, we also investigate the novel Punctured Convolutional coding for the system, indicating a trade-off between throughput and Bit Error Ratio (BER). The maximum 1120 Mbits/s throughput per band can be achieved at the expense of 6 dB Eb/No penalty, in contrast to the maximum 480 Mbits/s per band of the current standard Orthogonal-Frequency-Division Multiplexing (OFDM)-UWB (WiMedia specification v1.2). This research provides a potential solution for the system optimization, modulation and coding designs of a practical high-capacity UWBoF system.**

***Index Terms*—Ultra-WideBand, SCM/DWDM, Radio-over-Fiber, Orthogonal-Frequency-Division-Multiplexing, Optical-Frequency-Multiplication, Punctured Convolutional Coding.**

I. INTRODUCTION

ULTRA-WideBand (UWB) [1][2] is an attractive radio technology exhibiting low power consumption, low interference and high bitrate in short-range wireless communica- tions for the future 4G [3] and Bluetooth 3.0 WPAN systems [4]. UWB is defined as any radio signal with a fractional bandwidth of at least 0.20, or a 10-dB bandwidth of at least 500 MHz [2]. Now the UWB in the 60 GHz band included in the IEEE 15.3c (license-free, available 7 G Bandwidth) is interesting provided that the transmission reach is extended because the maximum spectral density is allowed from -41.3 dBm/MHz to 13 dBm/MHz, considered as a feasible solution for providing multi-Gbit/s WPAN system [5]-[6].

Ultra-WideBand (UWB) Radio over Fiber (UWBoF) [6]-[10], the unique integration of ROF and UWB, is a feasible solution for Fiber-To-The-Home (FTTH) access networks providing high-definition (HD) audio/video [11], Intelligent Transport System (ITS) [12], and so on. For UWB, the coverage is limited, typically smaller than 4 m at 200 Mbits/s, due to the low emitted PSD [2]. A method to enlarge the coverage is increasing the nodes of UWB signal at the expense of the cost. Fortunately, the optical fiber provides a low-cost solution to distribute the UWB signal to many BSs in a broadband RoF network [6]-[8]. Thanks to the ROF, it will make the BS very simple and provide enough bandwidth for the multi-Gbit/s requirement. However, we must overcome the problems in the design of broadband RF mixers, luckily optical mixing provides an attractive solution to take advantage of the large BW of the optical domain. Optical up-conversion for RF signals has been intensively investigated in the last decades because it allows one to centralize frequency-conversion

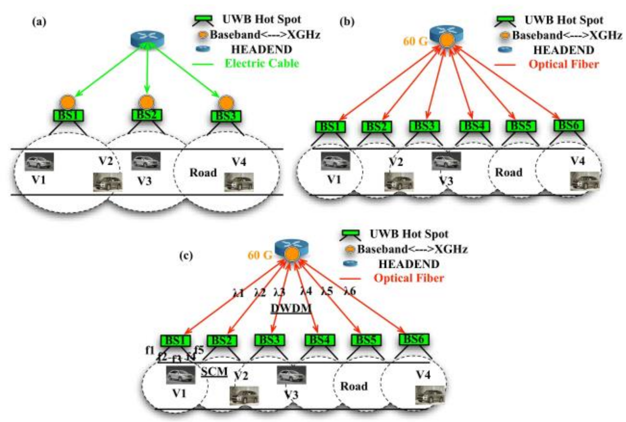

Fig. 1 UWBoF for ITS: a) UWB Transmission Based on Electric Cable, b) 60 GHz UWB Transmission Based on ROF, c) Proposed 60GHz UWBoF Based on SCM/DWDM.

Manuscript received July 10, 2013. This work was supported in part by the Japan Global Center of Excellence (GCOE) Programs. Xiaoan Huang, Assoc. Prof. Chika Sugimoto, and Prof. Ryuji Kohno are with the Division of Physics, Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan-240-8501. E-mail: [huang, chika, kohno]@kohnolab.dnj.ynu.ac.jp.

operation in the Headend to make different BSs very simple [13][14][15]. The ITS application is depicted in Fig. 1, only requiring the frequency up-conversion (Baseband - XGHz) in Headend to mitigate the BS complexity, by replacing the Electric Cable with Optical Fiber in Fig. 1 b).

In our proposal, to the best of our knowledge, we firstly employ the SCM/DWDM to the 60GHz UWBoF, achieving the high data rate and high-mobility requirements. OFDM-UWB is introduced to this system because OFDM has major advantage of its robustness against multi-path propagation, good spectral efficiency, high-data-rate capabilities between 55 and 480 Mbps, and low power consumption [2][16]. Furthermore, for the IR-UWB Radio over Fiber, there are some disadvantages especially for the high RF: 1) IR-UWB signals are more sensitive to nonlinear distortion for optical transmission [17]; 2) IR-UWB can not follow the channelization [11]. The basic idea of SCM/DWDM is shown in Fig. 1 c), where DWDM is utilized between the HEADEND and many BSs, and SCM is employed between BS and mobile users. SCM is a technology where multiple RF signals are multiplexed in the RF domain and then transmitted by a single optical wavelength, with high optical bandwidth efficiency and high dispersion tolerance in combination of DWDM [18]. Furthermore, novel modulation and coding are well designed in order to overcome the fiber-dispersion-induced penalty and improve the BER and throughput performance. This work targets to give an insight to the system optimization, novel modulation and coding for the future high-speed UWB systems in the 60 GHz band at the first time.

The rest of this paper is organized as follows. In Section II, the mathematical optimization of OFDM-UWBoF, OFM modulation, and SCM/DWDM is exhibited. In Section III, the proposed UWBoF system based on SCM/DWDM is presented. And in Section IV, we conclude the paper.

II. MATHEMATICAL OPTIMIZATION

A. Optimization of OFDM-UWBoF

1) Back-to-Back UWBoF:

The MB-OFDM RF signal Y_{RF} (t) is as follows:

$$Y_{RF}(t) = Re[V_{RF}\exp(j2\pi f_{RF}t + \theta(t)) \cdot \sum_{n=-N_{BW}/2}^{N_{BW}/2} C_n \exp(j2\pi n\Delta f(t - T_{GI}))] \quad (1)$$

It can be simplified into,

$$Y_{RF}(t) = V_{RF}\sum_{n=-N_{BW}/2}^{N_{BW}/2} |C_n|\, cos[(\omega_{RF} + n\Delta\omega)t - n\Delta\omega T_{GI} + \psi(t)] \quad (2)$$

We first consider the back-to-back UWBoF, but the nonlinearities of the DE-MZM must be considered:

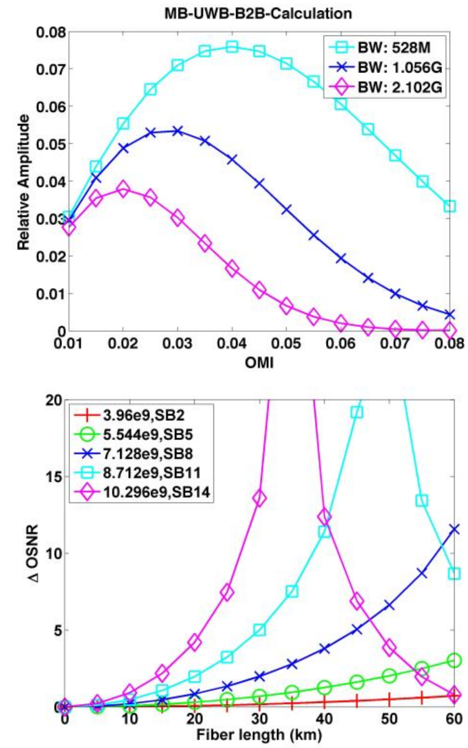

Fig. 2 Analytical Comparison: a) Optimized Modulation Index for MB-UWBoF; b) Impact of dispersion on MB-UWBoF, SubBand (SB).

$$E_{out} = E_{in} cos(\omega_{oc}t) \cdot cos[\sum_{n=-N_{BW}/2}^{N_{BW}/2} \pi m_{RF} cos((\omega_{RF} + n\Delta\omega)t - n\Delta\omega T_{GI} + \psi(t)) + \pi\frac{V_b}{V_\pi}] \quad (3)$$

And using the Bessel function expansions under the small signal analysis, it can be written as:

$$E_{out} = E_{in}J_1(\pi m_{RF})[J_0(\pi m_{RF})]^{N_{BW}-1} \cdot cos[(\omega_{RF} + n\Delta\omega)t - n\Delta\omega T_{GI} + \psi(t)] \quad (4)$$

where, ω_{oc}, ω_{RF}, m_{RF}, and Δf are the optical carrier frequency, RF frequency, the modulation index of RF (OMI), and 4.125 MHz, respectively.

2) Impact of Fiber Dispersion:

Fiber transfer function is as follows:

$$H(\omega) = \exp(\frac{1}{2}j\beta''\omega^2 L)\exp(-\alpha L/2) \quad (5)$$

$$\beta(\omega) = n(\omega)\omega/c = \beta_0 + \beta'(\omega - \omega_c) + \frac{1}{2}\beta''(\omega - \omega_c)^2 + \cdots \quad (6)$$

here, $\beta'' = -\lambda^2 D/(2\pi c)$, D, L, and α are the dispersion coefficient, fiber distance, and attenuation constant, respectively. So, for OFDM-UWBoF, the OSNR degradation can be expressed as [19]:

$$\Delta OSNR = [cos^2(\pi L f^2 D \lambda^2 / c)]^{-1} \quad (7)$$

According to the above calculation result, we first verify that the optimum modulation index may be chosen for different BWs, and the RF needs to be selected carefully in order to avoid the severe fiber dispersion-induced degradation, depicted in Fig. 2.

B. *NOVEL OFM MODULATION*

Radio-Over-Fiber, the unique blend of both optical and

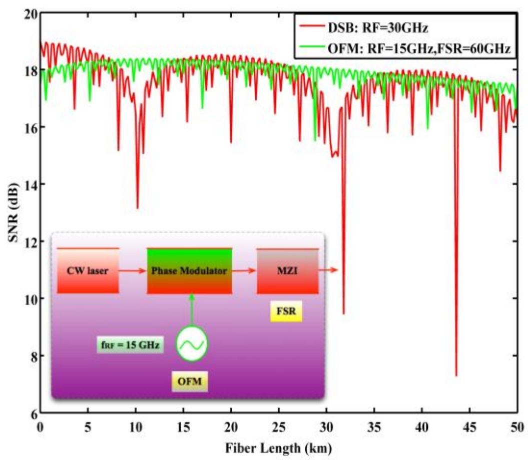

Fig. 3 Calculated OFM (greenline) vs. DSB (redline) for 60-GHz UWBoF.

wireless system, is the last mile for increasing the capacity and mobility as well as decreasing the expenses, especially in the millimeter wave (mm-wave) bands [20]-[21]. It is a cost-effective solution because it can consolidate most signal processing functions in the Headend. The main challenge of ROF is the generation and delivery of high-quality RF to the BaseStation (BS), while maintaining the BS simplicity [20]-[21]. Methods employing a laser with an external optical modulator, for example, Mach-Zehnder Modulator, have shown great potential for producing high-purity and high-frequency mm-wave bands [20]-[21]. Currently the 3 main optical up- conversion methods: DSB, SSB, OCS have their own draw- backs [22]-[23]. Many approaches for mixing or up-conversion of RF signals have been reported, either electronically or optically, such as utilizing Optical DSB [22][24][25], Single-SideBand (SSB) [24][25], and Optical Carrier Suppression (OCS) modulation [26][27][23].

- DSB:
  - Pros: simple and low price, only needs a single-arm modulator;
  - Cons: limited transmission distance, due to due to the fading effect.
- SSB:
  - Pros: dispersion tolerant;
  - Cons: not immune to noise and complex for receiver.
- OCS:
  - Pros: optical carrier reuse and allow a direct amplification just after the modulator;
  - Cons: need a complex electrical circuit to control the bias.

OFM Modulation, a very competitive candidate, has been used to up-convert low-frequency signal to a much higher frequency signal in the traditional ROF system reported in the paper [21]. However, to our knowledge, it has not yet employed to the UWBoF system. As is shown in Fig. 3, it is achieved by a Phase Modulator and a Mach-Zehnder-Interferometer (MZI) with the Free Spectral Range (FSR) in the Headend and a photo-detector in the BS. Fiber dispersion is very critical parameter for fiber communication, so for DSB case,

$$\begin{aligned} P_{DSB} &= J_1^2(\pi m_{RF})[J_0^2(\pi m_{RF})]^{N_{BW}-1} \\ &\cdot \; cos^2(\omega_{oc}\Delta t) \cdot cos^2(\omega_{LO2}\Delta t) \cdot 10^{-L_{op}/10} \quad (8) \end{aligned}$$

For OFM case,

$$\begin{aligned} P_{OFM} &= J_1^2(\pi m_{RF})[J_0^2(\pi m_{RF})]^{N_{BW}-1} \cdot cos^2(\omega_{oc}\tau_1) \\ &\cdot \; {J_2}^2[2m_{LO1} sin(\omega_{LO1}\tau_1/2)] \cdot 10^{-L_{op}/10} \quad (9) \end{aligned}$$

here, $m_{RF} = V_{RF}/V_\pi$, $\tau_1 = \tau + \Delta t$, $\tau = 1/FSR$, $L_{OP} = \alpha \cdot L$ and $\Delta t = D \cdot \Delta\lambda \cdot L$. Δt, D, α, L, and $\Delta\lambda$ are pulse spreading, dispersion, attenuation coefficient, transmission distance in fiber, and Spectral Width of the light source, respectively. In these equations, J is Bessel function of the first kind. Here, we design the parameters as follows: ω_{oc}: 193.1THz, ω_{LO1}: 15 GHz, ω_{LO2}: 30 GHz, D: 17 ps/nm·km, α: 0.2 dB/km, $\Delta\lambda$: 0.3 nm. According the Equations (8) and (9), the simulation shown in Fig. 3 is obtained, which verifies that OFM Modulation is more dispersion-tolerant even up to 50 km optical transmission distance, due to very slight loss and no large dips. Consequently, OFM Modulation is feasible and cost-effective solution for ROF even for 50 km optical transmission.

C. *NOVEL SCM/DWDM*

The blend of SCM and DWDM may provide a more flexible platform for high-speed optical transport networks with high optical bandwidth efficiency and high dispersion tolerance. SCM/DWDM has been utilized for the traditional ROF system [18]. However, as we know, SCM/DWDM has not been employed for the UWBoF system. Fig. 5 shows the SCM/DWDM scheme, where SCM (5 RFs) is employed between BS and mobile users, and DWDM (6 optical wave-lengths) is utilized between the HEADEND and many BSs. The SCM: 3.96, 5.544, 7.128, 8.712, and 10.296 GHz (Sub- bands 2, 5, 8, 11, and 14), spaced by 1.584 GHz. DWDM: 193.1, 193.3, 193.5, 193.7, 193.9, and 194.1 THz, spaced by 200 GHz). The numerical optimization has been discussed in the following:

Considering two optical waves, we can get the coupled equations describing XPM (Cross-Phase Modulation) [28]:

$$\begin{cases} \frac{\partial A_1}{\partial z} + \frac{1}{V_{g1}}\frac{\partial A_1}{\partial t} = (-i2\gamma P_2 - \frac{\alpha}{2})A_1 \\ \frac{\partial A_2}{\partial z} + \frac{1}{V_{g2}}\frac{\partial A_2}{\partial t} = (-i2\gamma P_1 - \frac{\alpha}{2})A_2 \end{cases} \quad (10)$$

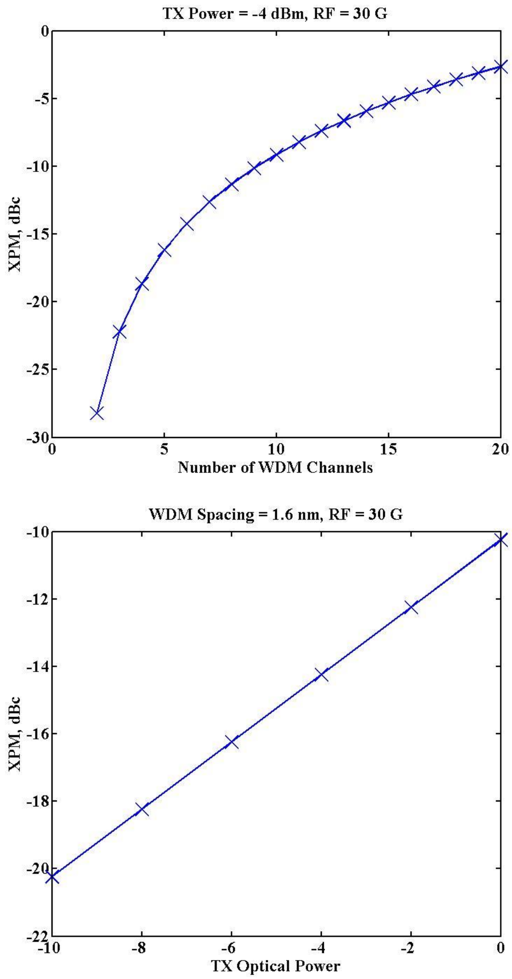

Fig. 4 Calculated XPM Optimization: Impact of the DWDM channel number and the TX optical power (6 DWDM channels).

then, we can obtain:

$$A_2(z,\tau_2) = A_2(0,\tau_2)\exp^{-\alpha z/2} \cdot \exp[-i2\gamma \int_0^{z_1} P_1(0,\tau_2 + d_{21}z)e^{-\epsilon z_1}dz_1] \quad (11)$$

After the normalization, the crosswalk can be expressed as follows:

$$XT_{XPM2} = \frac{-2\beta_2''\omega^2\gamma P_c}{(\alpha - j\omega d_{21})^2}\{[e^{-\alpha L}cos(\omega d_{21}L) -1+\alpha L] + j[(e^{-\alpha L}sin(\omega d_{21}L)+\omega d_{21}L]\} \quad (12)$$

where, α, γ, and V_{gi} (i = 1 or 2) are the fiber attenuation coefficient, the nonlinearity coefficient, and the group velocity, respectively, and $d_{21} = (1/V_{g2} - 1/V_{g1})$. According to the above Equation, the calculated XPM optimization can be obtained, depicted in Fig. 4. Hereby, the appropriate number of DWDM channels and TX optical power should be well designed to suit the system requirements, due to the above numerical analysis.

III. PROPOSED UWBOF SYSTEM BASED ON SCM/DWDM

A. PROPOSED A 60 GHZ UWBOF SYSTEM BASED ON SCM/DWDM

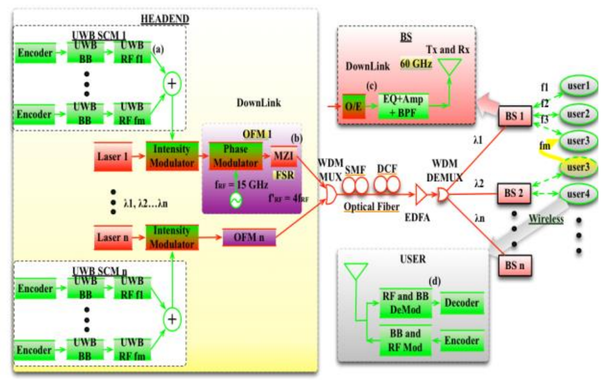

Fig. 5 Schematic Block Diagram of the 60 GHz OFDM-UWBoF Based on SCM/DWDM (the green: electrical link and the red: optical link). (SCM: 3.96, 5.544, 7.128, 8.712, and 10.296 GHz (Subbands 2,5,8,11 and 14), spaced by 1.584 GHz. DWDM: 193.1, 193.3, 193.5, 193.7, 193.9, and 194.1 THz, spaced by 200 GHz). BB: BaseBand, EQ: Equalization, Amp: Amplifier, BPF: Band-Pass Filter.

Block diagram of a 60GHz OFDM-UWBoF System Based on SCM/DWDM is shown in Fig. 5. For Downlink, from optical to wireless channel, at first in the Headend the UWB RF signal shown in Fig. 6 (a) is produced by MATLAB, then several UWB RF signals will be added into the Intensity-Modulator with an optical laser employing SCM technology. Followingly, the signal goes through the OFM Modulation with the MZI at point (b) exhibited in Fig. 6 (b), where the distance between the 2 main optical signals is 60 GHz. Here, DWDM technology will be utilized to fully exploit the optical channel

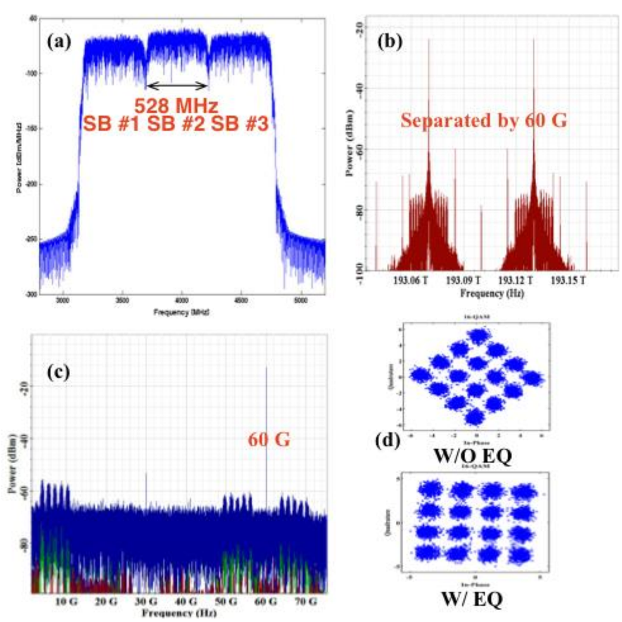

Fig. 6 Simulated Spectrum of the Proposed system depicted in Fig. 5. : a) UWB Band Group 1 generated by MATLAB: SB1, 2 and 3; b) Optical Modulation based on OFM; c) Optical DeModulation; d) Constellation of 16QAM.

bandwidth, employing a DWDM Multiplexer. After transmitting through a 30 km SMF with 17 ps/nm/km dispersion D, UWB RF signal is recovered by a photo-detector to fulfill the optical demodulation at point (c) in Fig. 6 (c). Followingly, the 60-G band UWB signal will pass through 5 m wireless channel, and can be received by the End User 1 and 2, and finally will be demodulated at point (d) in Fig. 6. The 16QAM constellations before and after Equalization are shown in Fig. 6 (d), exhibiting good performance after Equalization.

The OFDM-UWB signal shown in Fig. 6 (a) is generated by combining the three standard OFDM-UWB produced by MATLAB to support the UWB Band Group 1 [2]. The Sub-Band (SB) 1 (3.168-3.696 GHz, 3.432 GHz central frequency), SB 2 (3.696-4.224 GHz, 3.96 GHz central frequency) and SB 3 (4.224-4.752 GHz, 4.488 GHz central frequency) of the UWB Band Group 1 can be transmitted by utilizing the frequency-hopping. Here, for OFDM, the Cyclic Prefix, 1/4 of the symbol duration, is added in the front of the symbol to eliminate the inter-symbol interference from the previous symbol. The reason why we choose the OFDM-UWB is due to the high efficiency in capturing energy and the robustness to RF interference in multi-path environment [2][16].

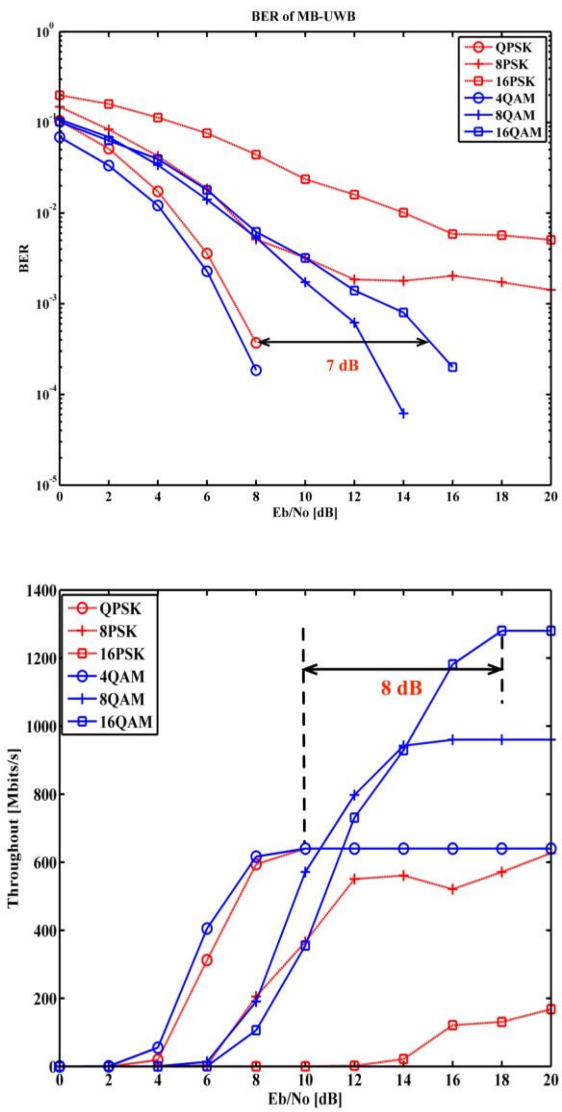

Fig. 7 BER and Throughput of different Baseband Modulations: PSK (red-dashed line) and QAM (blue-solid line).

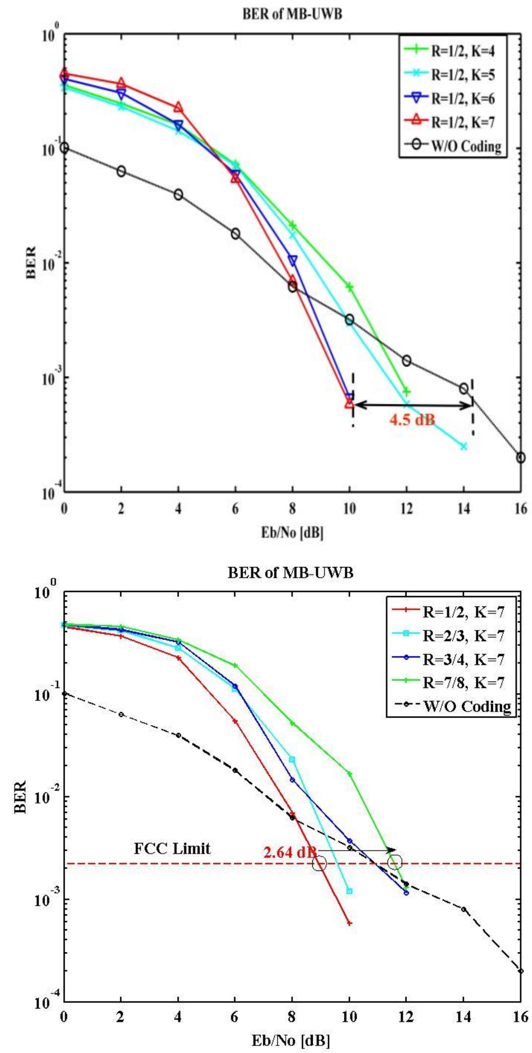

Fig. 8 BER for Code-Rate 1/2 with different K from 4 to 7, and for different CodeRates of 1/2, 2/3, 3/4 and 7/8, with the same K = 7.

The current OFDM-UWB standard (WiMedia specification v1.2) has just considered QPSK Baseband Modulation. Here, we employ different Baseband modulations for this system and analyze BER in Fig. 7. Basically, BER performance of 16QAM is worse, with 7 dB Eb/No penalty for the same BER 0.00037, compared with that of QPSK. As for other Baseband Modulations, for example 8QAM, it is not practical because that it is more susceptible to noise and the BER performance is close as that of 16QAM, while the bits per symbol of 8QAM is reduced in half. And for 8PSK and 16PSK, the BER performances are bad even when Eb/No is above 16 dB. Furthermore, based on the throughput analysis of Fig. 7, the throughput of 16QAM can be up to 1280 Mbits/s with 8 dB Eb/No penalty as a trade-off, while only 640 Mbits/s for QPSK and 4QAM. For 8QAM, the throughput is much smaller than

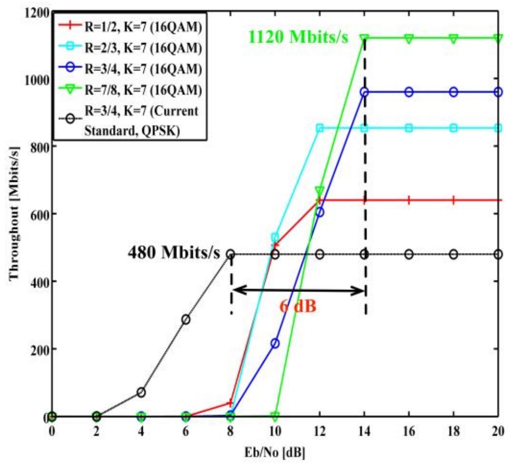

Fig. 9 BER for Code-Rate 1/2 with different K from 4 to 7, and for different CodeRates of 1/2, 2/3, 3/4 and 7/8, with the same K = 7.

that of 16QAM, though BER is slightly better than that of 16QAM. As a result, we should rather choose 16QAM as the Baseband Modulation due to the good BER quality and larger throughput performance.

B. NOVEL CODING

As we know, convolutional codes have powerful error correcting capabilities [28][29][30]. A well-known process for decoding convolutional codes is the Viterbi decoding, a maximum likelihood decoder, meaning that the output code word is always the one with the highest correct probability. Viterbi decoding is based on a trellis diagram with 2K1 states, which implies that the decoding complexity of the code is deeply relative to Constraint-Length K, since the Viterbi algorithm needs to keep track of 2K1 states. So, for convolutional codes, 2 key important parameters: Code-Rate R and Constraint-Length K must be considered. Furthermore, puncturing is an effective technique designed to produce the required R m/n from the basic mother-code R 1/2, which is reached by deletion of some bits in the encoder output [29][30]. On the one hand, the better BER performance can be obtained by designing the different K from 4 to 7, shown in Fig. 8. We can obtain that the BER performance of W/ coding with K = 7 is better, with 4.5 dB Eb/No improvement for the same BER 0.00057, compared with that of W/O coding. On the other hand, in order to analyze the system better, punctured convolutional codes of different R 2/3, 3/4, and 7/8 originated from the mother-code R 1/2 are designed for the system with the same K = 7, as shown in Fig. 8. Fig. 8 has shown that the BER performance of R = 7/8 is worse, with 2.64 dB Eb/No penalty for the same BER 0.0022 (FCC limit), compared with that of the mother-code R=1/2. Finally, we had better design the appropriate K and R, based on these simulations. For the former K, the larger K, the lower BER, while the more complexity for decoding; for the latter R, the larger R, the more throughput, while with more Eb/No penalty.

C. PERFORMANCE ANALYSIS

For this 60 GHz OFDM-UWBoF system, 16QAM Base-Band Modulation has been employed, based on the previous analysis. Besides the BER analysis, throughput is also key indicators for the overall system, as simulated in the Fig. 9. The maximum 1120 Mbits/s throughput per band can be achieved by employing the novel coding with R = 7/8 and K = 7, while at the expense of 6 dB Eb/No penalty, in contrast to the max 480 Mbits/s of current standard OFDM-UWB utilizing the coding with R = 3/4 and K = 7.

IV. CONCLUSION

In this paper, a thorough analysis of 60 GHz OFDM-UWBoF system integrating modulation and coding is firstly proposed, indicating the high optical bandwidth efficiency for the novel SCM/DWDM modulation, a cost-effective and dispersion-tolerant solution for the novel OFM modulation and a much larger throughput performance for the novel coding. We have successfully achieved the optical up-conversion of the OFDM-UWB signal to the 60 GHz band by employing the novel OFM modulation with much lower 15 GHz RF and obtained 3.36 Gbits/s throughput for the total 3 bands by designing the novel punctured convolutional coding with R = 7/8 and K = 7, meaningful for the future requirements of the HD audio/video, ITS, and so on. However, a MZI must be introduced to fulfill the optical up-conversion for the OFM modulation, increasing some hardware complexity in some aspects and 6 dB Eb/No penalty is also a big issue for the coding. As for the channel coding part, a Ultra Sparse LDPC Coding introduced in the newest version of the WIMEDIA 1.5 standard [31] should be also updated in our research. We believe that this work will be a feasible solution for the 60 GHz UWBoF system in the future 4G, WPAN and ITS application.

ACKNOWLEDGMENT

This work is supported by the Japan Global Center of Excellence (GCOE) Programs.

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