

60-GHz Ultra-WideBand Radio-Over-Fiber System Employing Modulation and Coding

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Abstract— We firstly propose a duplex 60-GHz Ultra-WideBand (UWB) Radio-Over-Fiber (ROF) System to extend the coverage for UWB communication systems. The novel Optical Frequency Multiplication (OFM) Modulation 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 Encoding 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). In the future, in order to figure out the bottleneck due to the aggregation of multi-BSs, we also will give a detailed analysis about the system network. This study provides a potential solution for the modulation and coding designs of a practical UWB-ROF system.

Index Terms—Radio-Over-Fiber (ROF), Ultra-WideBand (UWB), Orthogonal-Frequency-Division Multiplexing (OFDM), Optical Frequency Multiplication (OFM), Punctured Convolutional Coding.

I. INTRODUCTION

Radio-Over-Fiber, the unique blend of both optical and wireless systems, is the last mile for increasing the capacity and mobility as well as decreasing the expenses, especially in the millimeter wave (mm-wave) bands [1]-[8]. 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 [1]-[8]. Many approaches for mixing or up-conversion of RF signals have been reported, either electronically or optically, such as utilizing Optical DSB [2][3][4], Single-SideBand (SSB) [3][4], and Optical Carrier Suppression (OCS) modulation [5][6][7].

- DSB:
 - Pros: simple and low price, only needing a single-arm modulator

- Cons: limited transmission distance, 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.

Ultra-WideBand (UWB) [9] is an attractive radio technology exhibiting low power consumption, low interference and high bitrate in short-range wireless communications for the future 4G [10] and Bluetooth 3.0 WPAN systems [11]. 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 [9]. Now the UWB in the 60 GHz band 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 [12]-[15].

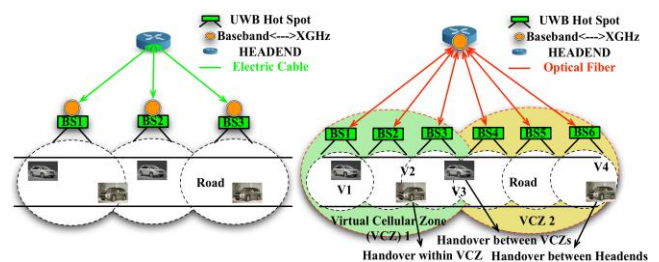


Fig. 1. UWB-ROF for ITS

UWB-ROF [14]-[21], 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 [17], Intelligent Transport System (ITS) [20], and so on. The ITS application is shown 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. Moreover, the major feature of traditional ROF for ITS in 60 GHz band is that there is almost zero dropping handover within the VCZ [20]. In this paper, 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 [9][16]. For UWB, the coverage is limited, typically smaller than 4 m at 200 Mbits/s, due to the low emitted PSD [9]. 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 [14]-[21]. 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 upconversion for RF signals have been intensively investigated in the last decades because it allows one to centralize frequency-conversion operation in the Headend to make different BSs very simple [22][23][24]. This work targets to give an insight to the novel modulation and coding for the future UWB systems in the 60 GHz band at the first time.

II. NOVEL MODULATION AND CODING

A. NOVEL MODULATION

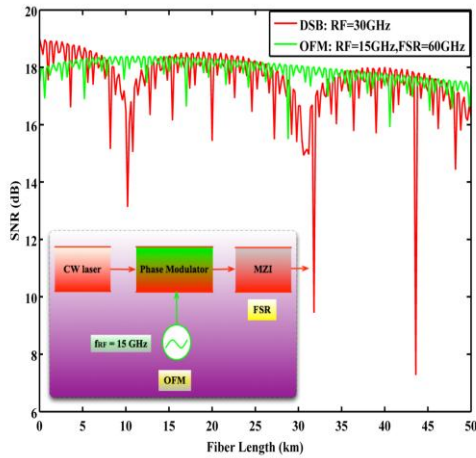


Fig. 2. OFM (green line) vs. DSB (red line)

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 [1]-[8]. Currently the 3 main optical up-conversion methods: DSB, SSB, OCS have their own drawbacks [2]-[7]. 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 [8]. However, to our knowledge, it has not yet employed to the UWB-ROF system. As is shown in Fig. 2, 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.

For OFM case,

$$P_{OFM} = A^2 \cdot \cos(\omega_c \tau_1) \cdot J_2(2\beta \sin(\omega_{RF} \tau_1 / 2)) \cdot 10^{-L_{OP}/10}, \quad (1)$$

Also, for DSB case,

$$P_{DSB} = A^2 \cdot \cos^2(\omega_c \Delta t) \cdot \cos^2(\omega_m \Delta t) \cdot 10^{-L_{OP}/10}, \quad (2)$$

Here,

- $\tau = 1 / FSR$, - delay introduced by FSR
- $\Delta t = D \cdot \Delta \lambda \cdot L$, - delay due to the fiber dispersion
- $\tau_1 = \tau + \Delta t$, - total delay
- $L_{OP} = \alpha \cdot L$, - optical loss

ω_c , ω_{RF} and ω_m are the optical frequency, RF of OFM, RF of DSB, respectively. For the SMF and laser parameters, D , α , L and $\Delta \lambda$ are the dispersion of SMF, attenuation coefficient, optical fiber length, and the laser line-width, respectively. In these equations, A is the amplitude, and J is Bessel function of the first kind. Here, we design the parameters as follows: $\omega_c = 193.1$ THz, $\omega_{RF} = 15$ GHz, $\omega_m = 30$ GHz, $D = 17$ ps/nm·km, $\alpha = 0.2$ dB/km, $\Delta \lambda = 0.3$ nm. According the Equations (1) and (2), the simulation shown in Fig. 2 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.

The OFDM-UWB signal shown in Fig. 3 is generated by

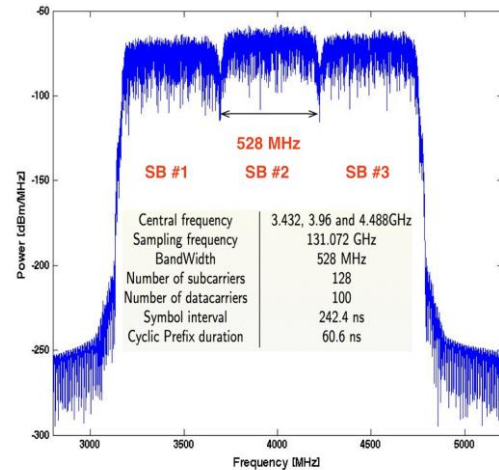


Fig. 3. UWB Parameters and Band Group #1 generated by MATLAB: SB #1, #2 and #3.

combining the three standard OFDM-UWB produced by MATLAB to support the UWB Band Group #1 [4]. 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

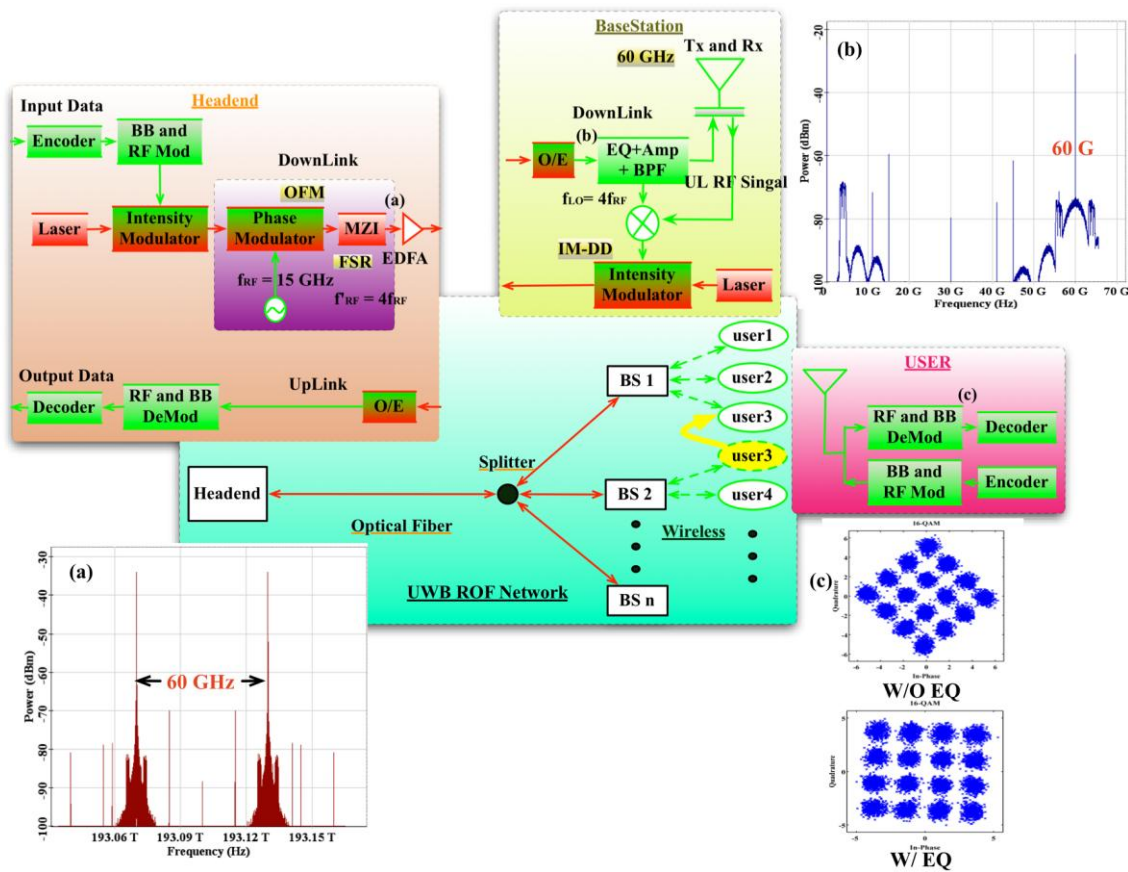


Fig. 4. Schematic Block Diagram of the Duplex 60 GHz OFDM-UWB ROF (the green : electrical link and the red: optical link) . BB: BaseBand, IM-DD: Intensity Modulation-Direct Detection, EQ: Equalization, Amp: Amplifier, BPF: Band-Pass Filter.

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 [9][16].

Block diagram of a Duplex 60GHz OFDM-UWB Radio-Over-Fiber System is shown in Fig. 4. For Downlink, from optical to wireless channel, at first in Headend the UWB RF signal is modulated by the Intensity-Modulator with an optical laser. Then, the signal goes through the OFM Modulation with the MZI at point (a) in Fig. 4, where the distance between the 2 main optical signals is 60 GHz. 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 (b) in Fig. 4. Following, 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 (c) in Fig. 4. The 16QAM constellations before and after Equalization are shown in Fig. 4(c), exhibiting good performance after Equalization. For UpLink (UL), from wireless to optical channel, the Local Oscillator (LO) signal f_{LO} from the uplink will down-conversion the incoming UL RF signal and consequently can allow a very simple

Intensity Modulation- Direct Detection (IM-DD), thus maintaining the BS very simple.

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. 5.

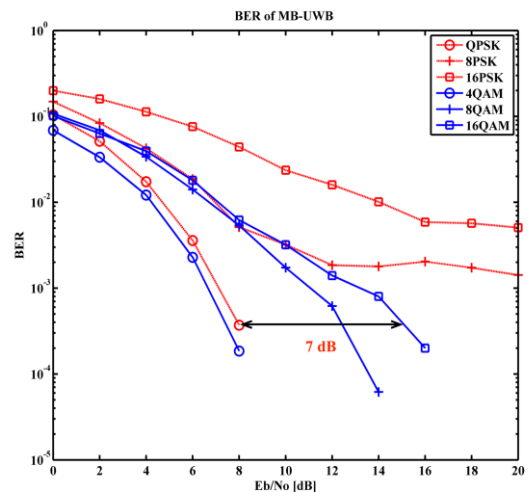


Fig. 5. BER of different Baseband Modulations: PSK (red-dashed line) and QAM (blue-solid line).

Basically, BER performance of 16QAM is worse, with 7 dB E_b/N_0 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 E_b/N_0 is above 16 dB. Furthermore, based on the throughput analysis of Fig. 6, the throughput of 16QAM can be up to 1280 Mbits/s with 8 dB E_b/N_0 penalty as a trade-off, while only 640 Mbits/s for QPSK and 4QAM. For 8QAM, the throughput is much

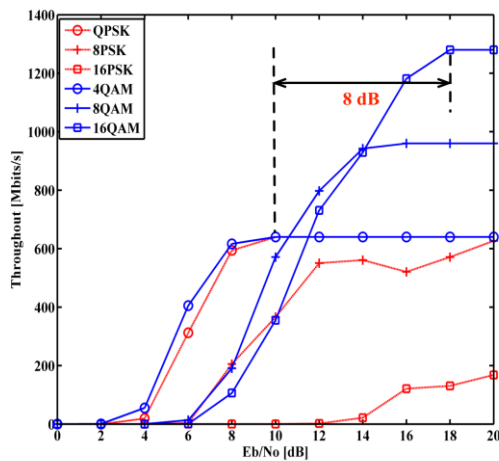


Fig. 6. Throughput of different Baseband Modulations: PSK (red-dashed line) and QAM (blue-solid line).

smaller than 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 [25][26][27]. 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 2^{K-1} 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 2^{K-1} 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 [26][27]. On the one hand, the better BER performance can be obtained by designing the different K from 4 to 7, shown in Fig. 7. We can obtain that the BER performance of W/ coding with $K = 7$ is better, with 4.5

dB E_b/N_0 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 2.65 dB E_b/N_0 penalty for the same BER 0.0013, 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 E_b/N_0 penalty.

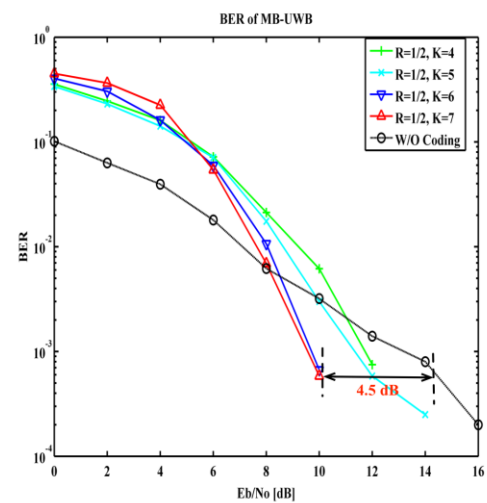


Fig. 7. BER for Code-Rate 1/2 with different K from 4 to 7.

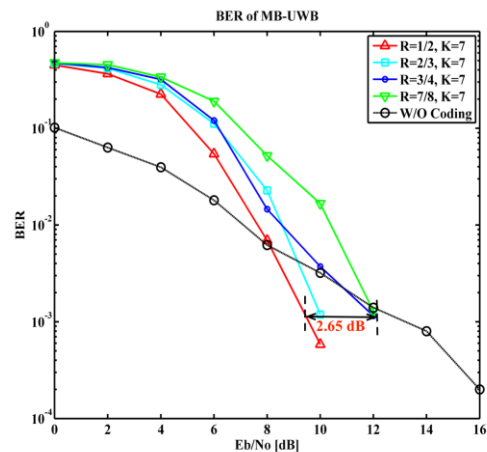


Fig. 8. BER for different CodeRates of 1/2, 2/3, 3/4 and 7/8, with the same $K = 7$.

III. PERFORMANCE ANALYSIS

For this 60 GHz OFDM-UWB ROF 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 E_b/N_0 penalty, in contrast to the max 480 Mbits/s of current standard OFDM-UWB utilizing the coding with $R = 3/4$ and $K = 7$.

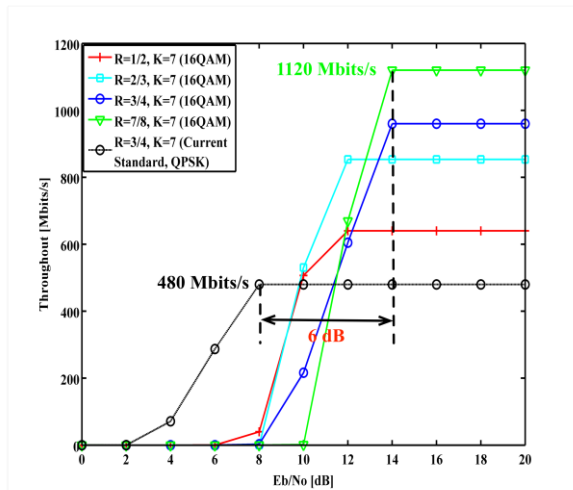


Fig. 9. Throughput for different CodeRates of 1/2, 2/3, 3/4 and 7/8, with the same $K = 7$.

IV. CONCLUSION

In this paper, a thorough analysis of 60 GHz OFDM-UWB-ROF system integrating modulation and coding is firstly proposed, indicating 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 E_b/N_0 penalty is also a big issue for the coding. Also, Impulse-Radio (IR)-UWB, a very practical UWB technology, is not yet considered as a contrast with the OFDM-UWB for ROF. In the future research, the detailed comparison between OFDM-UWB and IR-UWB for 60 GHz UWB-ROF should be achieved for the market application. Furthermore, Optical Code Division Multiple Access and Wavelength Division Multiplexing may be utilized to overcome the bottleneck problem for the uplink network in the future work. We believe that this work will be a feasible solution

for the 60 GHz UWB-ROF system in the future 4G and WPAN application.

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