Long-reach 60-GHz radio-over-fiber system based on turbo-coded OFDM

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Turbo-coded 1.25-Gb/s orthogonal frequency-division multiplexing (OFDM) signals in 60-GHz radio-over-fiber system are demonstrated. It can overcome impairments in fibers and extend transmission distance. Experimental results show that the transmission distance of turbo-coded OFDM signals at 1.25 Gb/s with coding (pure bit rate of 830 Mb/s) can be extended by over 30%.

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Long-reach optical access networks can increase bandwidth of customer units while simultaneously reducing the number of base stations[1]. Radio-over-fiber (RoF) technique can reduce cost of wireless access[1−21]. Previous works based on long-reach optical access networks focused on low frequency signals, such as Wi-Fi operating at 5.8 GHz[1]. High frequency signals over fiber were constantly discussed in studies on short-reach less than 30-km networks, especially in 60-GHz wireless access networks with huge bandwidth availability of over 7-GHz unlicensed band[6−10]. Therefore, the study on 60-GHz wireless signals over long-reach optical access networks has been proven interesting. Previous experimental results show that optical millimeter wave (mm-wave) signals generated by optical carrier suppression (OCS) manifested high-receiver sensitivity and largely reduced the bandwidth of optical and electrical components[13]. However, due to fiber dispersion, the transmission distance of optical mm-wave signals generated by OCS at 60 GHz has been limited. Theoretical analysis have shown that the maximum transmission distance is less than 40 km for 1-Gb/s on/off keying signal carried by a 60-GHz OCS mm-wave[14]. Using orthogonal frequency division modulation in tandem with single-sideband modulation, transmission distance limited by fiber dispersion was largely increased[9], but its scheme has been complicated. Channel codes can be introduced to improve transmission distance, but only few reports focused on this topic. Turbo codes serving as channel codes have been used to overcome the impairments in the simple configuration of RoF systems through direct detection (DD). The introduction of turbo codes has been known to reduce spectral efficiency because of the number of redundancy bits. In our experiment, we demonstrate the transmission of 1.25-Gb/s turbo-coded orthogonal frequency-division multiplexing (OFDM) signals with double-sideband transmission over a 180-km single mode fiber SMF-28 long-reach optical link. The maximum transmission distance at bit error rate (BER) of 2×10^{-3} is extended by over 30% by employing the turbo coding technique.

Figure 1 shows the principle of the RoF architecture with turbo codes and optical frequency quadruple scheme. At the central station, laser was used to generate continuous wave (CW) lightwaves. Then, we employed an external modulator to realize an all-optical up-conversion. A directional coupler (DC) biased Mach-Zehnder modulator (MZM) at top peak power to generate optical mm-waves with four times radio frequency (RF). Base-band data were then modulated on the optical mm-wave. A 50/100-GHz interleaver (IL) with one input port and two output ports was employed to separate the optical carrier and the second-order sidebands at the central station. Two second-order sidebands were filtered out in one output port, while the optical carrier was filtered out in the other output port. After transmission, the two peaks of the second-order sidebands exhibited impulses. They generated mm-wave signals at the quadruple repetitive frequency of the RF signal after detection

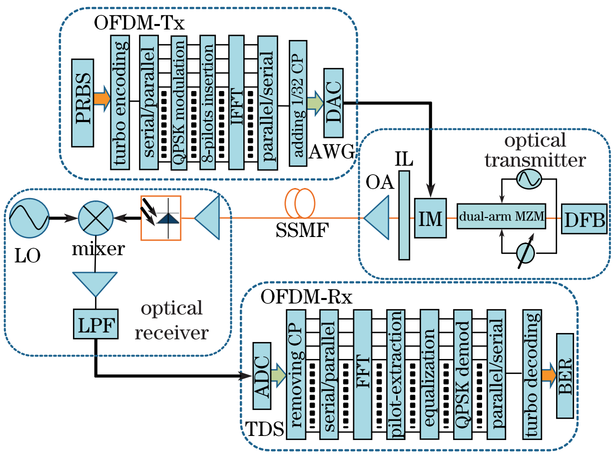

Fig. 1. Principle of turbo-coded OFDM signals transmission over SMF-28 in 60-GHz RoF long-reach system. Tx: transmitter; Rx: receiver; DFB: distributed feedback laser; SSMF: standard SMF; LPF: low-pass filter; DAC: digital-to-analog converter; ADC: analog-to-digital converter; AWG: arbitrary waveform generator; LO: local oscillator; PRBS: pseudo random binary sequence; QPSK: quadrature phase shift keying; OA: optical amplifier; IM: intense modulator; CP: cycle prefix; TDS: real time oscilloscope.

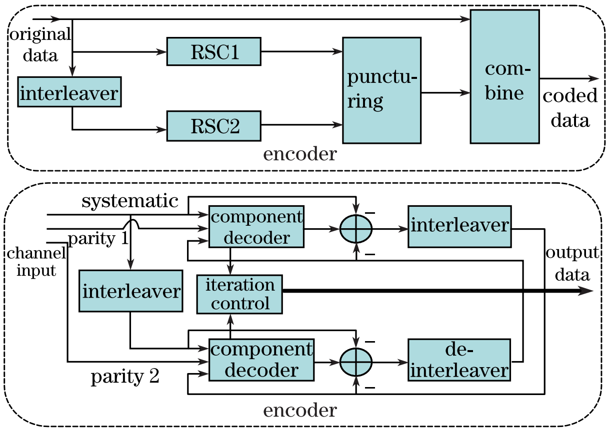

Fig. 2. Principle of turbo encoding and decoding techniques.

by the downlink high-speed receiver. The original data were encoded by a turbo encoder. Coded bits were then modulated by an OFDM modulator based on fast Fourier transform (FFT)/inverse fast Fourier transform (IFFT) to generate electrical waveform. At the receiver, optical OFDM signal was detected by a high-speed photodiode (PD) and then down-converted to electrical baseband OFDM signal. This signal is then sampled and demodulated into sequential symbols for de-interleaving and decoding.

The principle of turbo encoding and decoding techniques is depicted in Fig. 2. Turbo codes, working as forward error correction (FEC), can build up the relation between data bits and redundancy bits. If data bits transform into error bits, the decoder corrects the error bits by using redundancy information. The core idea for turbo codes is to permute the bits sequence randomly to realize random encoding corresponding to the Shannon theory on good FEC codes. Turbo codes are suitable for both random error bits and adjacent error bits due to their special design (i.e., by using an interleaver)[22−24].

Original data were divided into two component codes for the encoding of the same input bits. An interleaver was placed between the encoders. The length of the encoding frame was 1024 bits, matching the length of the interleaver. The generator vectors of the first recursive systematic convolution code (RSC1) was used to encode original data, while the second recursive systematic convolution code (RSC2) was used to encode interleaved data. Both were $g_0 = (1, 0, 11; 1101)$. Parity data after RSC1 and RSC2 were punctured at a rate of 0.25 and combined with the original data. The encoding rate of turbo codes employed in our experiment was about 0.66. Then, two component decoders were linked by the interleaver in a structure similar to that of the encoder. As seen in Fig. 2, RSC1 and RSC2 decoders have three inputs: 1) systematically encoded channel output bits, 2) parity bits transmitted from the associated component encoder, and 3) information from the other component decoder on the likely values of the respective bits. The said information from the other decoder is referred to as apriori information. Component decoders need exploit both the inputs from the channel and the apriori information.

We employed Max-Log-MAP algorithm in the decoder, as this algorithm is optimal in terms of minimizing the decoded BER. It could also simplify the MAP algorithm by transferring the recursions onto the logarithmic domain without reducing accuracy. The key parameters of the turbo coding technique are listed in Table 1. Turbo coding technique was used to recover the error bits by using redundancy bits.

Figure 3 shows the experimental setup for the long-reach RoF system with the 60-GHz turbo-coded OFDM signal. In the experiment, among the subcarriers of the OFDM signal, 200 subcarriers were used for data while 56 subcarriers were set to zero and used as guard interval. The guard interval (cyclic prefix) in the time domain was 1/8, referring to the 32 symbols in every OFDM frame. The OFDM signal, based on the quadrature phase shift keying subcarrier modulation scheme, was generated by a commercially arbitrary waveform generator (AWG). The Vp-p of the electrical OFDM signal was 1.6 V. The bit rates in our experiment were 1.25 Gb/s with codes of 830 Mb/s after decoding; 830 Mb/s was used for comparison. The CW lightwave generated from a commercial distributed feedback (DFB) laser was modulated by 15-GHz local oscillator (LO) signal with a DC-biased intensity modulator at top peak power. The first order sidebands are suppressed, as shown in Fig. 3(a). We then isolated the optical carrier by using the interleaver and modulated the turbo-coded OFDM signal on the 60-GHz optical mm-wave. The spectrum of this setup is illustrated in Figs. 3(b). The high-order sideband was 20 dB lower than the second-order sideband. Thus, the high-order sidebands have the minimal effects on the transmission of the optical mm-wave in SMF-28. The power inputted onto the fiber after erbium-doped fiber amplifier (EDFA) reached 6 dBm. The optical spectra of the optical mm-wave transmitted over 60, 120, and 180-km SMF-28 are shown in Figs. 3(c), (a), and (e), respectively. The optical mm-wave was pre-amplified by EDFA and filtered by a tunable optical band-pass filter (TOF) with a bandwidth of 0.5 nm. The optical mm-wave with turbo-coded OFDM signals was then opical-to-electrical converted with PIN PD with a 3-dB bandwidth of 60 GHz. The converted electrical OFDM signal was boosted by an electrical amplifier (EA) with a bandwidth of 10 GHz and centered at 60 GHz. An electrical LO signal at 60 GHz was generated by using a 1:4 frequency multiplier.

The electrical LO signal and a mixer were used to down-convert the electrical mm-wave signal. The down-converted OFDM signal was then filtered by a low-pass electrical filter with a bandwidth of 850 MHz, sampled by a commercially available real-time oscilloscope, and post-processed offline. The receiver constellations of the DFDM signals over 60, 120, and 180 km at

Table 1. Key Parameters for Turbo Code Technique in Experiment

FEC Type	Turbo Codes
Component Codes	Recursive Systematic Convolution Codes $g_0 = (1, 0, 11; 1101)$
Interleaver	1024-bit Random Interleaver
Component Decoder	Max-Log-MAP Decoder
Encoding Rate	0.66
Iterations	3

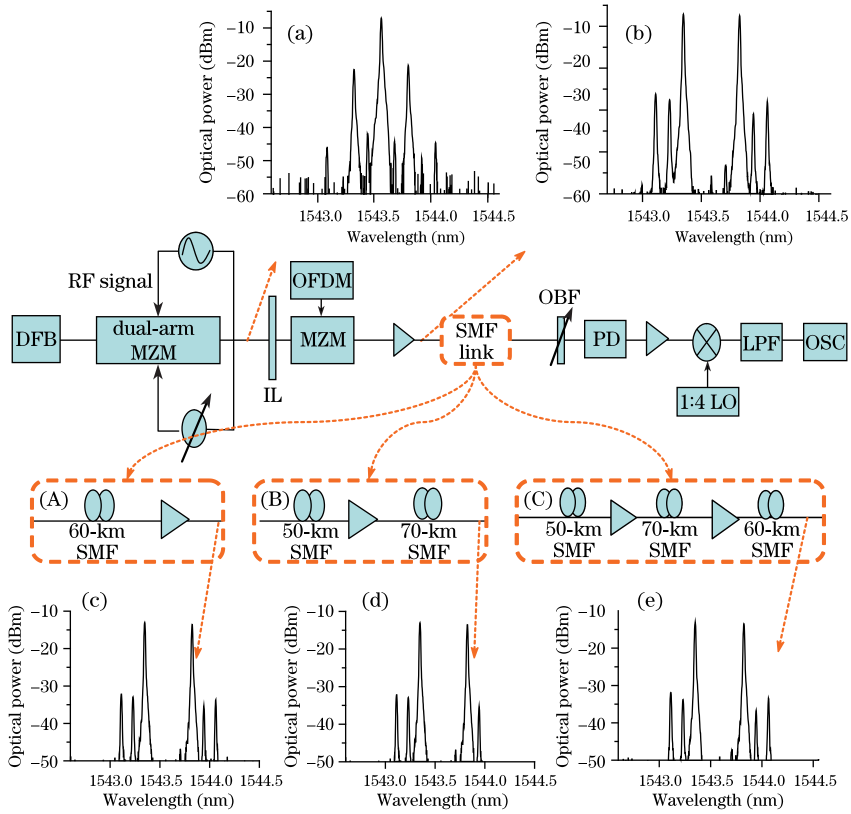

Fig. 3. Experimental setup for turbo-coded OFDM signals over 60-GHz RoF long-reach systems. OBF: optical band-pass filter; 1:4 LO: four times frequency multiplexer; LPF: electrical low-pass filter; OSC: real-time oscilloscope.

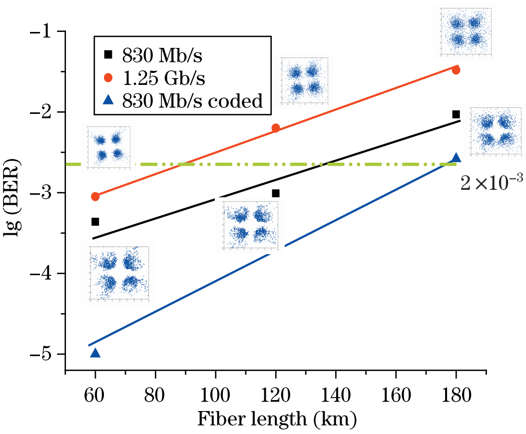

Fig. 4. BER curves of OFDM signals with and without turbo coding after transmission over 180 km.

1.25 Gb/s and 830 Mb/s are shown in Fig. 4. Distortions in the received constellation were mainly a result of impairments caused by fiber dispersion. Next, BER curves were measured for 1.25 Gb/s with coding (i.e., with pure bit rate of 830 Mb/s after decoding) and 830 Mb/s without coding over 180 km, as illustrated in Fig. 4. The distances of maximum transmission over SMF-28 for 1.25 Gb/s without coding, 1.25 Gb/s with coding (i.e., with pure bit rate of 830 Mb/s after decoding), and 830 Mb/s without coding at 2×10^{-3} were 85, 130, and 173 km, respectively. This suggests that >43 km, or over 30% transmission distance, could be extended by the turbo coding technique.

In conclusion, we demonstrate the transmission of 1.25-Gb/s OFDM signal with turbo codes at 60-GHz RoF system over a 173-km long-reach optical link. The turbo-coding technique demonstrates enhanced performance by combating impairments in fibers. Experimental results show that the maximum transmission distance at a BER of 2×10^{-3} can be extended by over 30% by employing the turbo coding technique.

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