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Simultaneous provision of wired service and dispersion-robust 60 GHz wireless service in radio-over-fiber system based on remote up conversion with electrical tones injection

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ABSTRACT

A novel and simple remote up conversion (RUC) scheme is proposed to provide wired service and 60 GHz dispersion-robust wireless service in a radio-over-fiber (RoF) system based on electrical tones injection (ETI). According to our knowledge, the RUC scheme with only one modulator is proposed for the first time. The ETI is utilized to simplify the traditional RUC scheme by simultaneously using one modulator for both the modulation of baseband data millimeter wave. Moreover, such scheme can provide both wired and wireless service without any additional device. Experimental results show that 2.5 Gbps wired service and 2.5 Gbps wireless service at 60 GHz are successfully delivered over 50 km SMF with power penalty less than 0.3 dB.

1. Introduction

The 60 GHz millimeter-wave (mm-wave) technology has attracted an increasing interest nowadays in the area of wireless personal area network (PAN) due to its advantages of high-throughput, high-security, and low-interference wireless connectivity [1]. Due to the oxygen absorption and the loss indicated in Friis transmission equation, the coverage of wireless signal at 60 GHz is restricted. To allow the ubiquitous wireless service coverage, radio-over-fiber (RoF) technology is proposed to extend the reach limitation of wireless signal [2–5]. However, the dispersion-induced impairments limit performance of RoF systems critically. Optical single sideband modulation schemes (OSSB) are proposed to overcome the distortion caused by dispersion (walk off effect or frequency selective fading) [5–9]. However most OSSB schemes require complicated structure and have imperfect features such as bandwidth limitation, nonlinearity and conversion loss.

Another kind of scheme named remote (frequency) up conversion (RUC) is proposed to reduce ISI induced by optical mm-wave transmission by generating the optical mm-wave in remote sites. Unlike OSSB, where the data signal is modulated on optical mm-wave in central offices (CO), the RUC mixes (or modulates) the data signal on optical mm-wave in the remote access point or remote gateway (GW) after fiber transmission. Thus the dispersion-induced walk-off effect can be avoided. In such scheme, two laser sources and two Mach–Zenhder modulators (MZMs) are individually used for baseband (BB) data modulation and blank optical mm-wave generation (without data modulation). In this paper, a simple RUC scheme based on electrical tones injection has been proposed to address both issues discussed above. Thanks to electrical tones injection, BB data modulation and blank optical mm-wave generation can share the same laser source and MZM. Moreover, such scheme can simultaneously provide wired service and 60 GHz wireless service for seamless convergence, which is beneficial for wireless service upgrading of existed passive optical networks (PON). Experimental results show that 2.5 Gbps wired service and 2.5 Gbps wireless service at 60 GHz are successfully delivered over 50 km SMF with power penalty less than 0.3 dB.

2. Operation principle and theoretical modeling

2.1. Operation principle

In this part, the operation principle of proposed RUC-ETI is described comparing with traditional RUC scheme. The traditional scheme is depicted in Fig. 1(i). The 1st wavelength (DFB-1) is for BB data modulation and the 2nd wavelength (DFB-2) is for blank 60 GHz optical mm-wave generation. The MZM-2 is biased at its null point to allow optical carrier suppression for optical frequency doubling. Then two wavelengths are coupled before fiber transmission with spectrum shown in Fig. 1(A). After fiber transmission, two

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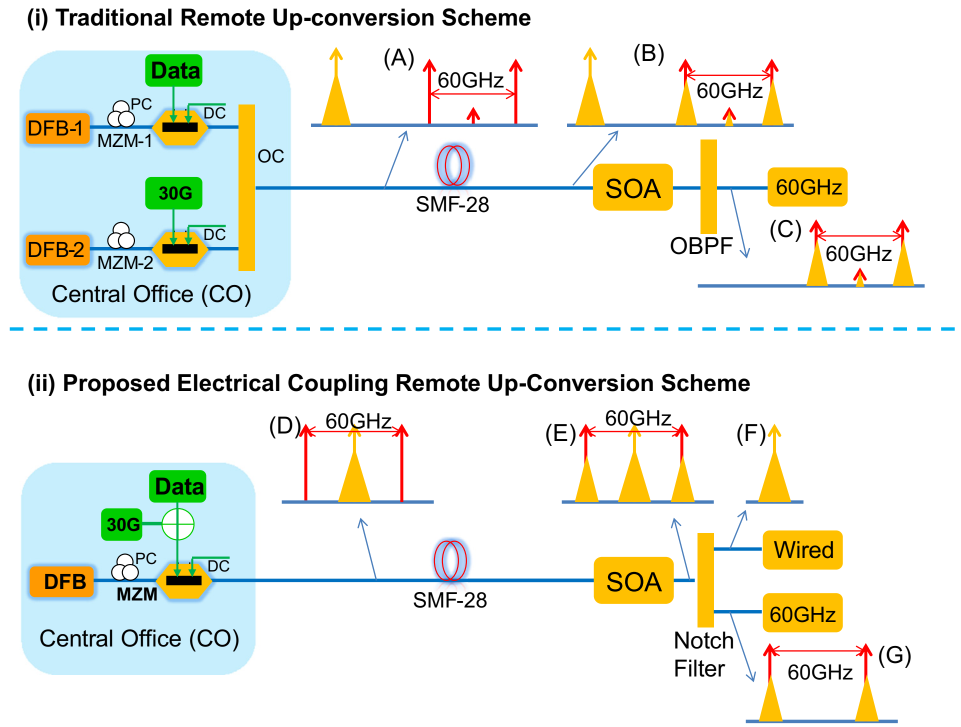

Fig. 1. The schematic of the remote up conversion based on electrical tone injection (RUC-ETI). DFB: distributed feedback laser; MZM: Mach–Zehnder modulator; PC: polarization controller; 30 G: 30 GHz local oscillator; DC: direct current bias; SMF-28: single mode fiber; SOA: semiconductor optical amplifier; wired: wired service; 60 GHz: 60 GHz wireless service.

wavelengths are boosted into a semiconductor optical amplifier (SOA) for cross gain modulation (XGM) process. BB data is then copied to blank optical mm-wave. The optical mm-wave with copied BB data is then filtered out to generate wireless signal via a photo-diode (PD).

The operation principle of RUC-ETI scheme is shown in Fig. 1(ii). The optical mm-wave is generated by electrical tones injection based on electrical coupling. The BB data and 30 GHz local oscillator (LO) are electrically coupled and then amplified to drive a MZM. The optical spectrum after the MZM is illustrated in Fig. 1(B). Having transmitted over fiber, the optical signal is boosted to a SOA for XGM. After the SOA, BB data carried by the optical central carrier is copied to two tones (optical mm-wave) to realize remote up conversion with optical spectrum shown in Fig. 1(C). The optical central carrier and sideband are then separated for wired and wireless services by an optical notch filter (ONF) with optical spectrum show in Fig. 1(D) and (E). Thus it is clear that the core idea of RUC-ETI is to use electrical coupling of BB data and LO signal to generate optical mm-wave sharing the same wavelength. By doing so, laser source and MZM can be shared and only one WDM channel is occupied. This will be beneficial for 60 GHz wireless service upgrading in passive optical networks (PON).

2.2. Theoretical analysis

In this section, a general mathematical model on RUC will be built up. The comparison of RUC-ETI and traditional RUC will be discussed based on this model. The optical carrier at the angular frequency ω_c with E_I amplitude can be expressed as:

$$E(t) = E_I \cos(\omega_c t) \tag{1}$$

The electrical data is modulated on the optical carrier via a pull–push operating Mach–Zenhder modulator and thus the optical data wavelength (ODW) can be expressed as:

$$\begin{aligned} E_m(t,z) &= \frac{E_I}{2}\left[\cos\left(\omega_c t + \pi\frac{\sqrt{2}}{2}S_{norm}(t) - \beta(\omega)z\right) + \cos\left(\omega_c t - \pi\frac{\sqrt{2}}{2}S_{norm}(t) - \beta(\omega)z\right)\right] \\ &= E_I \cos(\omega_c t - \beta(\omega)z)\cos\left(\pi\frac{\sqrt{2}}{2}S_{norm}(t)\right) \end{aligned} \tag{2}$$

where $\beta(\omega)$ denotes the propagation constant for different optical angular frequency components. $S_{norm}(t)$ denotes normalized presentation of BB signal and is deduced from:

$$S_{norm}(t) = S_{base}(t) + S_{bias} = \frac{S_{BB}(t)}{V_{\pi 1}} + \frac{V_{bias-a}}{V_{\pi 1}} \tag{3}$$

where $S_{BB}(t)$ is BB signal and $V_{\pi 1}$ is the switching voltage of MZ-*a*. V_{bias-a} is the bias voltage applied to MZ-*a*. Considering the pre-distortion with bias at linear point (V_π) of MZM field curve, and using pre-distortion function $y = (\sqrt{2}/\pi)\arccos(x)$, the output electrical field can be written as:

$$E_m = E_I S_{norm}(t)\cos(\omega_c t - \beta(\omega_c)z) \cong E_I[1 + S_{base}(t)]\cos(\omega_c t - \beta(\omega_c)z) \tag{4}$$

We replace $\beta(\omega)$ with $\beta(\omega_c)$ because that the dispersion-induced distortion are not significant for low data modulation bandwidth (2.5 Gbps) and short fiber distance (50 km). The *E*-field of the pure optical mm-wave (without data modulation, OMW) can be expressed as:

$$E_p(t) = \sqrt{\overline{P}_{LO}}\cos(\omega_o + 0.5\omega_{LO})t + \sqrt{\overline{P}_{LO}}\cos[(\omega_o - 0.5\omega_{LO})t + \theta] \tag{5}$$

where $\overline{P}_{LO}$ is the average power of OMW and $\sqrt{\overline{P}_{LO}}$ presents its amplitude. And $\omega_o \pm 0.5\omega_{LO}$ are the optical frequency of upper and lower sidebands of OMW, and θ is the phase difference in between which is induced by dispersion. The XGM process can be then