Wavelength Reuse in an RoF Link Based on CS-DSB, Coherent Detection and DSP

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***Abstract*— Wavelength reuse in a bidirectional radio over fiber link based on carrier-suppressed double-sideband (CS-DSB) modulation, coherent detection, and digital signal processing (DSP) is proposed and experimentally demonstrated. At the center office, an optical single-sideband with carrier (OSSB+C) signal is generated and distributed to the base station. The wavelength reuse at the base station is implemented by directly modulating the downstream OSSB+C signal with an upstream signal based on CS-DSB modulation. The modulated upstream signal is sent to the center office where a coherent receiver and a DSP unit are used to recover the upstream signal by eliminating the crosstalk from the downstream signal, and at the same time, to cancel the phase noise from the laser source. An experiment is performed. The transmission of a 16-QAM downstream microwave vector signal and a 16-QAM upstream microwave vector signal over a 17-km single-mode fiber (SMF) is experimentally demonstrated. The power penalty caused by the wavelength reuse is less than 0.8 dB.**

***Index Terms*— Digital signal processing (DSP), laser phase noise, radio over fiber (RoF), optical coherent detection, phase noise cancellation (PNC), wavelength reuse.**

I. INTRODUCTION

THE distribution of radio signals over an optical fiber or radio over fiber (RoF) is a technique to achieve cost-effective wireless access. In a RoF link, all high-cost signal processing units are centralized in a shared center office (CO) [1], making the base stations (BSs) simplified with reduced cost. To further minimize the capital and operational costs at the BSs, a bidirectional RoF link with wavelength reuse at the BSs could be employed, to avoid the use of an additional laser source. Numerous schemes to reuse a wavelength from a downstream optical signal for upstream transmission were proposed, which include injection locking of a Fabry-Pérot laser diode [2], gain-saturation of a semiconductor optical amplifier (SOA) [3] or a reflective SOA (RSOA). However, the analog bandwidth of an SOA or RSOA is very limited (typically around 1 GHz). In addition, in [2], to achieve a stable injection locking, the injected power must be large and the wavelength must be within the injection bandwidth. Furthermore, in [2] and [3], to minimize the crosstalk from the downstream signal, the extinction ratio of the downstream signal has to be very low, which would deteriorate the performance for the downstream transmission. To avoid the crosstalk from a downstream signal [2], [3], modulation formats with no amplitude modulation, such as phase modulation (QPSK or DPSK, for example), could be used for downstream transmission to facilitate the erase of the downstream signals [4]. However, since a downstream signal was phase modulated, direct detection with the assistance of a delay-line interferometer has to be used. Thus, the date rate for the downstream is not transparent to the downstream link [4]. To solve this problem, two schemes were proposed [5], [6]. In the first scheme, two orthogonally polarized light waves, both are phase modulated by a downstream signal at a polarization modulator (PolM) for the downstream transmission, are utilized for wavelength reuse [5]. In the second scheme, an intensity-modulated optical signal was polarization multiplexed with a pure optical carrier and then transmitted to the receiver [6]. The pure optical carrier is separated using a polarization demultiplexer and used for wavelength reuse in the BS. The main limitation of the schemes in [5] and [6] is that polarization multiplexing cannot be implemented to double the data rate due to the occupation of the other polarization state. To increase the data rate, recently we have proposed a RoF link with wavelength reuse based on polarization multiplexing and coherent detection [7]. The main limitation of the scheme in [7] is that optical double sideband with carrier (DSB+C) modulation has to be used, which may decrease the optical energy efficiency.

In this letter, wavelength reuse in a bidirectional RoF link based on carrier-suppressed double-sideband (CS-DSB) modulation, coherent detection and digital signal processing (DSP) is proposed and experimentally demonstrated. For the downlink, optical single-sideband with carrier (OSSB+C) modulation is employed and the modulated optical signal is transmitted to a BS. At the BS, one portion of the OSSB+C signal is sent to a photodetector (PD) where the downstream microwave signal is detected and radiated to free space via an antenna. The other portion of the OSSB+C signal is used for wavelength reuse, which is done by sending the OSSB+C signal to a single-electrode Mach-Zander modulator (MZM) that is biased at the null point, to realize CS-DSB modulation. At the output of the MZM, a CS-DSB signal carrying the upstream signal and the crosstalk due to the re-modulation of the downstream signal are obtained and sent back to the CO. To recover the upstream signal while eliminating the crosstalk from the downstream signal, coherent detection using a local oscillator (LO) laser source followed by DSP is employed. With an algorithm performed by the DSP unit, the upstream signal is recovered, and at the same time, the phase noise introduced from the laser source is eliminated. The proposed

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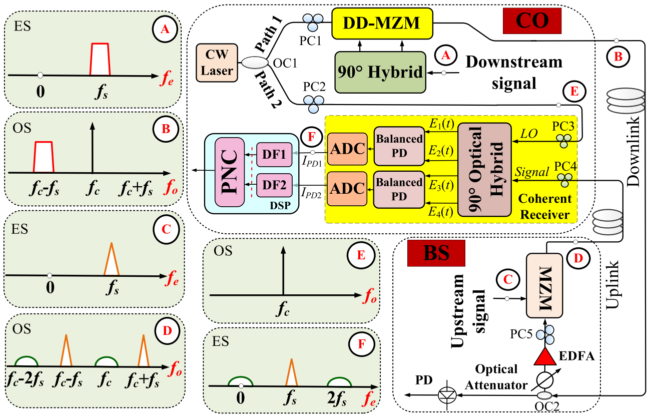

Fig. 1. Schematic of the proposed RoF link with wavelength reuse based on CS-DSB modulation, coherent detection and DSP. DF1: digital filter 1, DF2: digital filter 2.

scheme is experimentally demonstrated. The transmission of a 2.5-Gbps 16-QAM downstream microwave vector signal and a 2.5-Gbps 16-QAM upstream microwave vector signal over a 17-km SMF is experimentally demonstrated. The power penalty caused by the wavelength reuse is measured to be less than 0.8 dB.

II. PRINCIPLE OF OPERATION

Fig. 1 shows the schematic of the proposed bidirectional RoF link with wavelength reuse based on CS-DSB, coherent detection and DSP. At the CO, a continuous-wave (CW) light wave from a laser source is divided into two paths by a 1×2 optical coupler (OC1), with the light wave from the upper path sent to a dual-dive Mach-Zander modulator (DD-MZM). A rectangular 16-QAM microwave vector signal is applied to the DD-MZM through the two RF ports via an electrical 90° hybrid. At the output of the DD-MZM, an OSSB+C signal consisting of the optical lower sideband and the optical carrier (point B) is obtained which is then sent to the BS over an SMF [8]. At the BS, the downstream optical signal is divided into two portions by a second 1×2 optical coupler (OC2). One portion of the received optical signal is applied to a PD to generate a downstream microwave vector signal. The other portion of the received optical signal is amplified by an erbium-doped fiber amplifier (EDFA) and sent to an MZM where it is modulated by an upstream pre-coded microwave vector signal. The MZM is biased at the null point to generate a CS-DSB signal [9]. At the output of the MZM, an optical signal with four frequency components is obtained (point D). The double sideband signal (the triangles) is generated by modulating the optical carrier by the upstream signal, and the other two signals (two semicircles) are the crosstalk due to the re-modulation of the optical lower sideband carrying the downstream signal by the upstream signal. Then, the optical signal at the output of the MZM is sent to a coherent receiver at the CO through another SMF. An LO signal which is the light wave from the lower path of OC1 is also applied to the input of the coherent receiver. At the outputs of the coherent receiver, two electrical signals are obtained which are sampled and sent to a DSP unit where the upstream signal is recovered with the crosstalk from the downstream signal eliminated and the phase noise from the laser source cancelled.

Mathematically, the OSSB+C signal at the output of the DD-MZM is given by

$$E_d(t) = \frac{\sqrt{2P_s}}{2} e^{j[\omega_c t+\varphi_{c1}(t)]} \times \left[e^{j\frac{\pi S_{RF-down}(t)}{V_{\pi 1}}} + e^{j\frac{\pi \hat{S}_{RF-down}(t)}{V_{\pi 1}} - j\frac{\pi}{2}} \right] \quad (1)$$

where P_s is the optical power at the input of the DD-MZM, ω_c is the angular frequency of the optical carrier ($\omega_c = 2\pi f_c$), $S_{RF-down}(t)$ is the downstream microwave vector signal, $\hat{S}_{RF-down}(t)$ is the Hilbert transform of $S_{RF-down}(t)$, $V_{\pi 1}$ is the half-wave voltage of the DD-MZM, and $\varphi_{c1}(t)$ is the phase term of the transmitter laser source. The center frequency of the downstream microwave vector signal is f_s and the 3-dB bandwidth is B. The DD-MZM is biased at the quadrature point.

The OSSB+C signal is sent to a BS, where one portion is directly detected by a PD to generate the downstream microwave vector signal, and the other portion is sent to the MZM to which a star 16-QAM pre-coded microwave vector signal (upstream) is applied. Here, we assume the center frequency and the bandwidth of the upstream microwave are also f_s and B. In practice, the center frequency and the bandwidth of the downstream signal and upstream signal can be different. The MZM is biased at the null point. At the output of the MZM (point D), the optical carrier and downstream signal are fully suppressed. In addition, since the optical carrier and lower sideband signal are both modulated by the upstream microwave vector signal, an optical signal occupying four frequency bands are obtained (point D). The frequency band for the optical double sideband is from $f_c + f_s - B/2$ to $f_c + f_s + B/2$ and $f_c - f_s - B/2$ to $f_c - f_s + B/2$ while the frequency band for the crosstalk is from f_c-B to $f_c + B$ and $f_c - 2f_s - B$ to $f_c - 2f_s + B$. For a microwave vector signal, the center frequency f_s is much larger than the bandwidth B, thus, there is no overlap between the spectra of the double sidebands and the crosstalk.

The upstream optical signal at the output of the MZM is given by

$$E_{up}(t) = \sqrt{L_{s1}} E_d(t) \sin\left(\pi S_{RF-up}(t)/2V_{\pi 2}\right) \quad (2)$$

where $S_{RF-up}(t)$ is the upstream pre-coded microwave vector signal, $V_{\pi 2}$ is the half-wave voltage of the MZM, and L_{s1} is the link loss of the downlink. Here, the upstream pre-coded microwave vector signal is expressed as

$$S_{RF-up}(t) = r_m \cos(\omega_s t + \theta_n), \quad m = 1, 2, \ldots, M_1; \quad n = 1, 2, \ldots, M_2 \quad (3)$$

where ω_s is the angular frequency of the RF carrier, $\{r_m, 1 \leq m \leq M_1\}$ denotes the set of M_1 possible amplitudes while $\{\theta_n, 1 \leq n \leq M_2\}$ is the M_2 possible phases of the RF carrier that convey the transmitted information.

At the CO, the upstream optical signal from the BS is coherently detected at the coherent receiver to which an LO signal is applied. The LO signal is generated by taping part of the light wave from the transmitter laser source (point E).

The optical field at the output of the LO is given by

$$E_{LO}(t)=\sqrt{2P_{LO}}e^{j[\omega_c t+\varphi_{c2}(t)]} \tag{4}$$

where P_{LO} is the optical power and $\varphi_{c2}(t)$ is the phase term.

After coherent detection [10], two output photocurrents are obtained, which are given by

$$\begin{aligned} I_{PD1}(t) &= C\cdot S_{RF-up}(t)\cdot[\cos(\varphi_c(t))+\sin(\varphi_c(t))] \\ &\quad + C\cdot S_{RF-up}(t)\begin{bmatrix}(\pi \hat{S}_{RF-down}(t)/V_{\pi 1})\cos(\varphi_c(t)) \\ -(\pi S_{RF-down}(t)/V_{\pi 1})\sin(\varphi_c(t))\end{bmatrix} \end{aligned} \tag{5}$$

$$\begin{aligned} I_{PD2}(t) &= C\cdot S_{RF-up}(t)\cdot[\sin(\varphi_c(t))-\cos(\varphi_c(t))] \\ &\quad + C\cdot S_{RF-up}(t)\cdot\begin{bmatrix}(\pi S_{RF-down}(t)/V_{\pi 1})\cos(\varphi_c(t)) \\ +(\pi \hat{S}_{RF-down}(t)/V_{\pi 1})\sin(\varphi_c(t))\end{bmatrix} \end{aligned} \tag{6}$$

with $C = \pi R L_h\sqrt{P_s P_{LO} L_{s1} L_{s2}}/V_{\pi 2},\ \varphi_c(t) = \varphi_{c1}(t)-\varphi_{c2}(t)$ where L_h is the link loss caused by 90° optical hybrid and L_{s2} is the link loss of the uplink. As can be seen from (5) and (6), the first term is the upstream microwave signal which is affected by the phase noise, while the second term is the crosstalk due to the re-modulation of the downstream signal. Apparently, the optical upstream signal and the crosstalk are down-converted to the microwave frequency band (point F). The frequency band for the first term is from f_s-$B/2$ to f_s+$B/2$, while the frequency band for the crosstalk is from *0* to +B and $2f_s$-B to $2f_s$+B. Then, the two output photocurrents ($I_{PD1}(t)$ and $I_{PD2}(t)$) are sampled and sent to a DSP unit for further processing. Since $f_s >> B$, the spectra of the crosstalk and the upstream microwave signal have no overlap, a bandpass filter can be used to select the upstream microwave signal to filter out the crosstalk. In the DSP unit, the upstream signal is selected by a digital filter,

$$I_1 = C\cdot S_{RF-up}(t)[\cos(\varphi_c(t))+\sin(\varphi_c(t))] \tag{7}$$

$$I_2 = C\cdot S_{RF-up}(t)[\sin(\varphi_c(t))-\cos(\varphi_c(t))] \tag{8}$$

Both the signals are affected by the phase noise $\varphi_c(t)$. To cancel the phase noise, a simple algorithm given by

$$I_0 = I_1^2 + I_2^2 = C^2 r_m^2\cos(2\omega_s t+2\theta_n)+C^2 r_m^2 \tag{9}$$

is applied. As can be seen, the first term is free from the phase noise. But, the amplitude is multiplied by $\mathrm{r}_\mathrm{m}^2$and the phase is $2\theta_n$. If the upstream microwave vector signal is pre-coded, the impact from $\mathrm{r}_\mathrm{m}^2$and $2\theta_n$ can be eliminated. For example, if the possible amplitudes (r_m) of the pre-coded signal are 1 and $\sqrt{2}$, then the possible amplitudes (r_m^2) for the recovered signal are 1 and 2. Again, if the possible phases (θ_n) of the pre-coded signal are $\pm\pi/16$, $\pm5\pi/16$, $\pm9\pi/16$, $\pm13\pi/16$, the possible phases in the recovered signal would be $\pm\pi/8$, $\pm5\pi/8$, $\pm9\pi/8$, $\pm13\pi/8$, and the impact on the recovered signal is eliminated. Fig. 2 shows the constellations for the pre-coded 16-QAM signal and corresponding recovered standard star 16-QAM signal with the amplitude of r_m^2 and phase terms of $2\theta_n$.

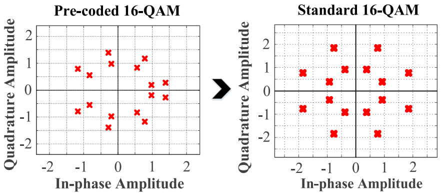

Fig. 2. The constellations for the pre-coded 16-QAM and its corresponding standard star 16-QAM with an amplitude of r_m^2 and a phase of $2\theta_n$.

III. EXPERIMENT

An experiment based on the setup shown in Fig. 1 is conducted. At the CO, a CW light wave from a tunable laser source (TLS, Yokogawa AQ2201) operating at 1550.008 nm (The corresponding frequency (f_c) is 193.413 THz) with a linewidth of 1 MHz and an optical power of 10.0 dBm is split into two paths by OC1 with a splitting ratio of 60:40 (60% for Path 1 and 40% for Path 2). In Path 1, a 625 MSymbol/s (2.5 Gbps) downstream standard rectangular 16-QAM microwave vector signal (EVM: 3.0%) with a center frequency of 5.4 GHz (f_s) is applied to the DD-MZM. An OSSB+C signal is obtained at the output of the DD-MZM and is transmitted over a 17-km SMF to the BS. The downstream signal is then divided into two portions by OC2 with a splitting ratio of 50:50. One portion of the OSSB+C signal with an optical power of -6.1 dBm is directly detected at the PD (Nortel PP-10G, PIN responsivity: 0.88 A/W) to generate the downstream microwave vector signal. The other portion is firstly amplified by an EDFA (EDFA-C-26G-S, noise figure: 5 dB, gain: 23 dB, the optical power at the output of the EDFA: 10 dBm). In the experiment, an optical attenuator is placed before the EDFA to control the optical input power to the EDFA. The amplified signal is then sent to the MZM via a PC (PC5) for wavelength reuse. Note that the EDFA can be placed in the CO if a high sensitivity EDFA is used. A 625 MSymbol/s (2.5 Gbps) upstream pre-coded 16-QAM microwave vector signal with an EVM of 9.21% at 5.4 GHz is applied to the MZM. The value of the EVM is selected assumming the EVM of the signal at the transmitter of the wireless terminal is 4% and a degradation in EVM is 5% due to the wireless transmission. A CS-DSB signal carrying the upstream signal and the crosstalk at the output of the MZM is generated and then transmitted back to the CO over another 17-km SMF. In Path 2, the CW light wave is sent to the LO port of the coherent receiver with a power of 5.75 dBm. The upstream signal with an optical power of −17.2 dBm is coherently detected at the coherent receiver (Discovery Semiconductors DP-QPSK 40/100 Gbps Coherent Receiver Lab Buddy). Two electrical signals (I_{PD1}, I_{PD2}) at the outputs of the coherent receiver are obtained which are sampled by a Digital Storage Oscilloscope (Agilent DSO-X 93204A) and the sampled signal are then sent to the DSP unit to recover the upstream microwave signal, and at the same time, to cancel the phase noise from the light source. Fig. 3(a) shows the spectrum at one of the two outputs of the coherent receiver (point F, I_{PD1}). As can be seen, both the upstream signal and crosstalk are down converted to microwave frequency bands and there is no overlap between the spectra of the upstream

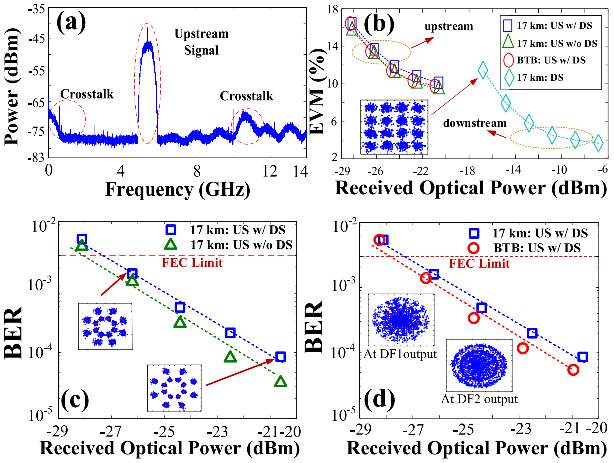

Fig. 3. (a) Spectrum of the electrical signal at the first output port of the coherent receiver (I_{PD1}), (b) EVM measurements at different received optical power levels for the downstream signal and upstream signals, (c) and (d) BERs at different received optical power levels for the upstream star 16-QAM microwave vector signal. US w/o DS: upstream signal without downstream signal (optical carrier only). US w/ DS: upstream signal with downstream signal. BTB: US w/ DS: back to back transmission of upstream signal with downstream. DS: downstream signal.

signal and crosstalk. In the DSP unit, the crosstalk is filtered out by a digital filter.

The error vector magnitudes (EVMs) at different received optical power levels for the recovered rectangular 16-QAM downstream microwave vector signals with a transmission distance of 17 km are measured, which are shown in Fig. 3(b). As can be seen, when the received optical power is -16.8 dBm, the EVM of the rectangular 16-QAM is -11.4% which is less than12.5%, the EVM specified in the 3GPP standard [12]. The constellation of the rectangular 16-QAM is also shown.

For the upstream, to evaluate the transmission performance and to verify the effectiveness of the DSP unit for the cancellation of the phase noise, we measure the EVMs and the estimated BERs for the recovered upstream 16-QAM microwave vector signals versus the received optical power are measured [11], which are shown in Fig. 3(b), (c) and (d). In estimating the BERs, we assume the noise after the digital phase noise cancellation (PNC) module is a stationary random process with Gaussian statistics. Three different situations are considered: 1) the reused optical signal is a pure optical carrier for upstream transmission (fiber length: 17-km SMF); 2) the reused optical signal is carrying a downstream microwave vector signal for back-to-back transmission, 3) the reused optical signal is carrying a downstream microwave vector signal for upstream transmission (fiber length: 17-km SMF). The constellations of the recovered upstream star 16-QAM microwave vector signals for the third situation are shown in Fig. 3(c). It can be seen that when the received optical power is as low as -26.2 dBm, the constellations are still clear which confirms the effectiveness of the PNC. The BER at this power level is estimated, which is less than 3×10^{-3}. By using a state-of-the-art forward error correction (FEC) technique (overhead 6.7%), error-free transmission can be ensured. As can be seen in Fig. 3(c), the power penalty caused by the wavelength reuse is as small as 0.8 dB. Thus, the wavelength reuse has small impact on the performance of the upstream transmission. The power penalty caused by the fiber transmission is also measured, which is 0.8 dB, as shown in Fig. 3(d). As a comparison, the constellations without PNC, measured at the outputs of two digital filters, DF1 and DF2, as shown in Fig. 1, are shown in Fig. 3(d). The quality of the signals is much poorer although the optical power is -20.6 dBm, which is higher than -26.2 dBm.

IV. CONCLUSION

Wavelength reuse in a RoF link based on CS-DSB modulation, coherent detection and DSP was studied. The crosstalk due to the re-modulation of the downstream OSSB signal and the phase noise introduced from the laser source were cancelled thanks to the use of coherent detection and DSP. The power penalty caused by the wavelength reuse and fiber transmission was measured to be less than 0.8 dB, which was small and has negligible impact the upstream signal transmission. The transmission of a 2.5-Gbps rectangular 16-QAM downstream microwave signal and a 2.5-Gbps star 16-QAM upstream microwave signal over a 17-km SMF was demonstrated. By using a state-of-the-art FEC technique, error-free transmission of both the upstream and downstream signals could be achieved. Compared with a common-public-radio-interface RoF link, the key advantage of the proposed scheme is that the cost and complexity of a BS in the proposed RoF link is lower.

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