



Polarization multiplexing based duplex radio-over-fiber link for millimeter wave signal transmission to a ring of multiple radio access units

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Abstract: A radio-over-fiber (RoF) distributed antenna system (DAS) architecture is proposed, where millimeter wave (mm-wave) signals are transmitted to four different radio access units (RAUs) arranged in a ring topology. The proposed architecture transmits duplex data of 128 Mb/s to each RAU in both downlink (DL) and uplink (UL) directions. The radio frequency (RF) signals are transmitted by polarization multiplexing a multi-wavelength source. Millimeter-wave signals at a frequency of 25 GHz are generated at each RAU using remote heterodyne detection. The proposed architecture provides increased coverage while maintaining good bit error rate (BER) results.

Key words: Radio over fiber; Millimeter wave; Radio access units

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1 Introduction

The last decade has seen an enormous growth in the development of high-bandwidth mobile data applications and in the number of mobile customers. The increase in the number of users and in the bandwidth demand per user has forced service providers to explore higher frequencies that lie in the mm-wave region. High frequency communication coupled with large bandwidth demand requires small cells that are lightened by multiple RAUs (Thomas et al., 2015b). Radio-over-fiber (RoF) technology provides an effective solution by taking the low-loss, light weight, large bandwidth, and cost-effective optical fiber link closer to the mobile subscriber in a classic passive optical network (PON). The radio access units (RAUs)

are connected to a central unit (CU) through optical fiber and the subsequent PON can improve wireless coverage by accomplishing diversity gain (Monteiro et al., 2010). Simplified RAUs and the cost-effective deployment of fiber cables are vital for the execution of profitable PONs (Mohamed et al., 2008; van Veen and Houtsma, 2017).

Cost reduction in RoF systems may be achieved by simplifying the RAU (Tang and Pan, 2016). Optical carrier reuse (OCR) is a common technique that has been widely explored to achieve simplified RAUs along with achieving full-duplex transmission (Thomas et al., 2015a). OCR enables a centralized architecture where all the optical sources are located at the CU. The uplink (UL) electronic signal at the RAU is transmitted by reusing the optical carrier received from the CU. Therefore, minimum signal processing and no wavelength management are required at the RAUs (Gulistan and Ghafoor, 2015).

Wavelength reuse and multi-wavelength

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generation scheme for bidirectional RoF signal transmission has been experimentally demonstrated in Hsueh et al. (2011). However, the requirement of multiple narrow-band filters makes the scheme complex and cost inefficient. A similar approach has been followed in Ghafoor and Hanzo (2011), where sub-carrier multiplexed (SCM) 64-QAM signals have been transmitted in a bidirectional link to two separate RAUs. In Cui et al. (2013) and Shao and Yao (2013), wavelength reuse has been experimentally demonstrated for bidirectional data transmission by implementing polarization modulation in the downlink (DL) direction and intensity modulation in the UL direction. A dual parallel Mach-Zehnder modulator (MZM) was used in Zhang et al. (2014) to generate two first-order sidebands and modulate the center wavelength with the downstream baseband data. At the base station (BS), one of the sidebands is used for up-converting the baseband data to 18 GHz by performing heterodyne detection in the photodetector, while the other sideband is used to transmit the upstream data from the BS to the central office. The architectures proposed in Cui et al. (2013), Shao and Yao (2013), and Zhang et al. (2014) transmit signals to only a single RAU. In a recent study, a dual polarization MZM is used to modulate the signal along one of the polarization axes while the signal along the other axis is left unmodulated (Tang and Pan, 2016). At the RAU, data is extracted from the modulated polarization state, whereas the unmodulated polarization state is used for UL signal transmission. Although the technique is simple and cost effective, it transmits data to only a single RAU. Furthermore, the transmission distance is short due to the high frequency of the electronic modulating signal.

Against this background, we propose a scheme that employs polarization multiplexing along with multiple wavelength generation from a single laser source for the transmission of RoF signals to multiple RAUs. The multiple RAUs are arranged in a ring architecture (Fig. 1). The motivation of the proposed scheme is to achieve high cost efficiency while maintaining high capacity and coverage. As can be seen in Fig. 1, the architecture is composed of four RAUs that are connected through fibers in a ring topology. The length of fiber between two successive RAUs is kept at 2 km. At the CU, multiple optical carriers are generated and one of the

polarization states of each optical carrier is intensity modulated with the DL RF signal. At each RAU, the RF signal is up-converted to mm-wave using heterodyne detection. Furthermore, the unmodulated polarization state is intensity modulated with the UL RF signal.

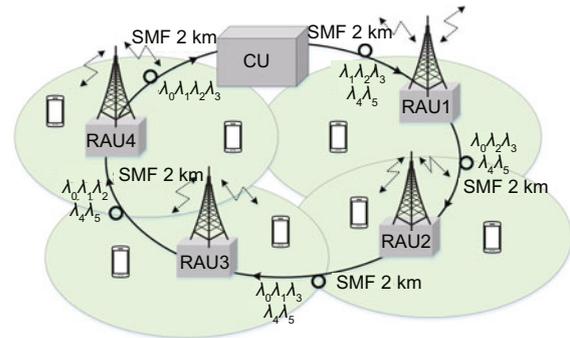


Fig. 1 Proposed radio-over-fiber (RoF) ring architecture (CU: central unit; SMF: single mode fiber; RAU: radio access unit)

The contribution of this paper is summarized below: The proposed architecture employs polarization multiplexing along with coherent multiple wavelength generation for duplex transmission of mm-wave signals to four different RAUs in a ring architecture.

We have performed a simulation study using the commercial tool known as OptSim.

2 Physical layer design of the proposed ring architecture

Fig. 2 shows the physical layer design of the architecture shown in Fig. 1.

2.1 Coherent multiple optical carrier generation

To generate multiple coherent optical carriers at the CU, a continuous wave (CW) laser diode is directly modulated using a sinusoidal signal of frequency $f_m = 12.5$ GHz. As a result of the laser diode's nonlinear response to a high-power electrical drive signal, multiple sidebands are generated around the center wavelength of the laser diode (Iezekiel, 2008). The instantaneous drive current I_d flowing through the diode due to the application of the sinusoidal signal may be represented as (Iezekiel,

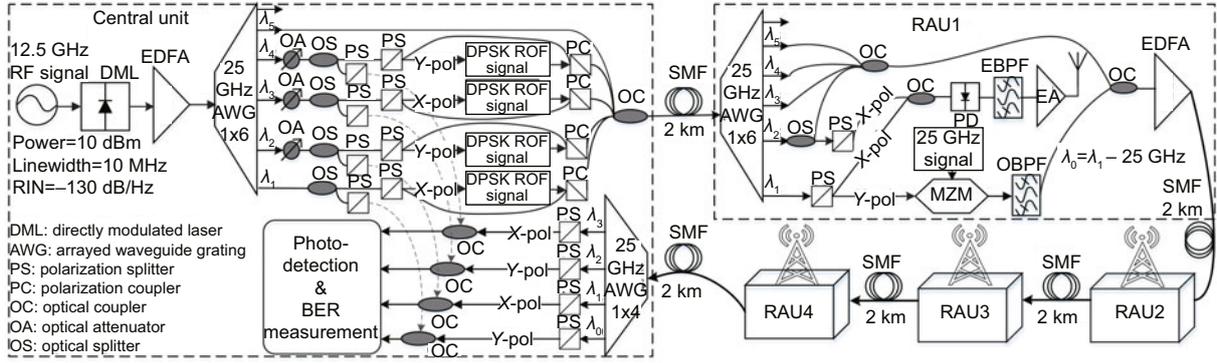


Fig. 2 Physical layer design of the proposed ring architecture (EDFA: erbium doped fiber amplifier; X-pol: X-polarization; Y-pol: Y-polarization; SMF: single mode fiber; MZM: Mach-Zehnder modulator; PD: photodetector; OBPf: optical bandpass filter; EBPF: electrical bandpass filter; EA: electrical amplifier; RAU: radio access unit)

2008)

$$I_d = I_b[1 + m \cos(\omega_m t + \varphi_m)]. \quad (1)$$

In the above equation, I_b is the bias current flowing through the diode due to the application of a DC bias voltage, and ω_m and φ_m are the frequency and phase of the applied sinusoidal modulating signal, respectively. The sinusoidal signal of frequency $f_m = 12.5$ GHz is superimposed on the DC bias voltage to directly modulate the laser. The quantity m in Eq. (1) is the modulation index of direct modulation and may be written as

$$m = \Delta I / (I_b - I_T). \quad (2)$$

Here, I_T is the laser diode's threshold current and ΔI is the deviation of the laser current from the bias current due to the application of modulating sinusoidal signal f_m . If we neglect the effect of chirping in the laser diode, the center frequency of the optical output of the diode ω_L remains fixed. The electric field at the output of the laser diode can be written as (Iezekiel, 2008)

$$E_L(t) = E_0 \sqrt{1 + m \cos(\omega_m t + \varphi_m)} \cdot e^{j(\omega_L t + \phi_L)}. \quad (3)$$

Here, E_0 is the amplitude of the output electric field, and ϕ_L and ω_L represent the phase and center frequency of the electric field, respectively. With the application of a sinusoidal signal to the laser diode, the output electric field $E_L(t)$ is composed of multiple frequencies due to nonlinear response of the diode. The discrete multiple frequencies are generally known as sidebands and are located at frequencies $f_n = f_L + n f_m$, where $n = 0, \pm 1, \pm 2, \pm 3, \dots$

and $f_L = 193.1$ THz is the central frequency of the laser (Hangauer et al., 2014). Generally, the sidebands have low optical powers compared to the center wavelength. However, the optical power of the sidebands may be increased by increasing the amplitude of the sinusoidal drive signal, which is equivalent to increasing the modulation index m of direct modulation. Therefore, the output electric field $E_L(t)$ of the diode after direct modulation may be written as (Hangauer et al., 2014)

$$E_L(t) = \text{Re} \left(\sum E_{L,n} e^{j2\pi(f_L + n f_m)t} \right). \quad (4)$$

In the above equation, $E_{L,n}$ represents the electrical field of the n^{th} -order sideband. In our simulation, multiple sidebands having suitable powers were generated by increasing the amplitude of the applied sinusoidal signal. The resulting spectrum at the output of the directly modulated laser is shown in Fig. 3a. It can be observed that the sidebands have a frequency difference of 12.5 GHz, which is equal to the frequency of the sinusoidal modulating signal. These sidebands have enough optical power to be used as separate optical carriers for signal transmission over fiber. It may also be observed from Fig. 3a that apart from the desired optical sidebands, there are spurious sidebands in the spectrum. These spurious sidebands are generated as a result of high-frequency direct modulation of the laser diode (Iezekiel, 2008).

2.2 Central unit

The output of the laser described by Eq. (4) is amplified using an erbium-doped fiber amplifier

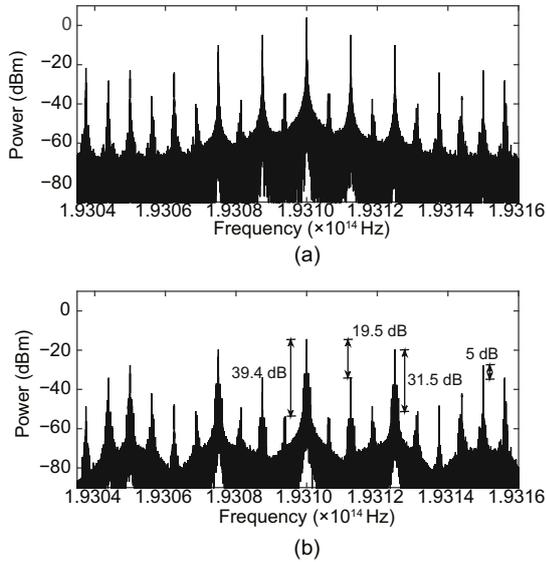


Fig. 3 Optical spectra of the unmodulated and modulated WDM signal: (a) spectrum at the output of the laser diode at CU; (b) spectrum of the modulated DL WDM signal at the output of CU (CU: central unit; WDM: wavelength division multiplexed; DL: downlink)

(EDFA) having a gain of 20 dB and a noise figure of 4 dB. The amplified signal is fed into a 1×6 arrayed waveguide grating (AWG) filter having a channel spacing of 25 GHz. Each channel of the AWG exhibits Gaussian-shaped filtering with a 3-dB bandwidth of 20 GHz. At the output of the AWG, five optical sidebands having a frequency difference of 25 GHz are obtained. As shown in Fig. 2, these optical carriers are labeled as λ_1 , λ_2 , λ_3 , λ_4 , and λ_5 . An optical power splitter (OS) is used to divide each optical carrier into two paths. The carrier in one of the optical paths will be used for processing the UL signals transmitted by the RAUs, as discussed in the next section. A polarization splitter (PS) is used in the second path to split the optical carriers λ_1 , λ_2 , λ_3 , and λ_4 into the two orthogonal polarization states denoted as X -pol and Y -pol (Fig. 2). The X -pol of λ_1 and λ_3 and the Y -pol of λ_2 and λ_4 are modulated with a differential phase shift keying (DPSK) signal having a data rate of 128 Mb/s and a carrier frequency of 500 MHz. The modulated and unmodulated polarization states are combined using a polarization combiner (PC). The polarization multiplexed signals λ_1 , λ_2 , λ_3 , and λ_4 as well as the unmodulated carrier λ_5 are coupled using an optical coupler (OC) (Fig. 2). Before being coupled, the optical powers of all the carriers are equalized

using an optical attenuator (OA). The higher power carriers λ_2 , λ_3 , and λ_4 are attenuated to reduce the effect of intensity-dependent phase noise known as cross-phase modulation (XPM). The phase noise imposed by XPM is converted to amplitude noise when composite optical signals travel through dispersive fiber (Chen and Way, 2004). If the powers of the optical carriers are not equalized, XPM will have a variable effect on each optical carrier. The resulting wavelength division multiplexed (WDM) signal at the output of the CU is shown in Fig. 3b. It may be observed from Fig. 3b that the odd-indexed sidebands and the spurious sidebands are suppressed by the AWG filter used at the CU. To observe the extent of suppression, the optical sideband suppression ratios (OSSR) for different sidebands are also shown in Fig. 3b. The data-modulated WDM signal is transmitted toward RAU1 using a standard single mode fiber (SMF). To consider the effect of polarization mode dispersion (PMD), the differential group delay of the fiber is kept at 0.2 dB/km.

As mentioned earlier, the center frequency of the DPSK RF signal used to modulate the optical carriers at the CU is kept low. Transmitting a low-frequency RF signal significantly reduces the effect of dispersion induced power fading. As discussed in Schmuck (1995), the dispersive SMF results in a frequency-dependent transfer function of the RoF link. At the output of a photodetector, the power of the RF signal P_{rf} used to modulate an optical carrier of power P_{op} that is transmitted over SMF of length L may be written as (Schmuck, 1995)

$$P_{rf} \propto \cos \left[\pi L c D \left(\frac{f_{rf}}{f_{op}} \right)^2 \right]. \quad (5)$$

Here, f_{rf} is the frequency of the RF signal, f_{op} is the frequency of the optical carrier, D is the dispersion parameter of the fiber, and c denotes the speed of light. It may be observed from Eq. (5) that the effect of power fading for low-frequency RF signals is observed after a very long length L of fiber.

2.3 Radio access unit

The polarization multiplexed WDM signal is received at RAU1 after traveling through a 2-km SMF. At each RAU, two optical carriers having a frequency difference of 25 GHz are required to generate mm-wave signal using heterodyne detection (Ghafoor and

Hanzo, 2011). Therefore, each RAU employs a 1x6 AWG filter with the same parameters as the AWG employed at the CU. At RAU1, λ_1 is split into X -pol and Y -pol states using a PS (Fig. 2). The second optical carrier used for heterodyne detection at RAU1 is λ_2 , which is first split into two paths using an OS. The signal in one of the paths is split into X -pol and Y -pol states, while the signal in the other path is coupled with the remaining optical carriers λ_3 , λ_4 , and λ_5 . To perform heterodyne detection, the X -pol of λ_1 and λ_2 are coupled using an OC and given as input to a high-speed photodetector having a responsivity of 0.9 A/W. The coupled signal at the input of the photodetector is shown in Fig. 4, where the OSSRs of the optical carriers are also mentioned. It may be observed from Fig. 4 that the unwanted optical sidebands have significant powers and may result in degradation of the RF signal at the output of the photodetector. However, these sidebands are located at large frequency spacings compared to the bandwidth of the RF signal, and can therefore be filtered out to some extent. An electrical bandpass filter (EBPF) is used at the output of the photodetector to filter out the mm-wave signal generated as a result of the photodetector's square-law detection. The EBPF is centered at a frequency of 25.5 GHz and has a 3-dB bandwidth of 3 GHz. Therefore, a mm-wave signal centered at a frequency of 25.5 GHz and modulated with a data rate of 128 Mb/s is generated at RAU1.

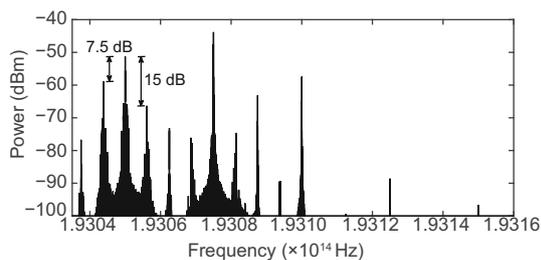


Fig. 4 Spectrum of the signal at the input of the photodetector at RAU-1 (RAU: radio access unit)

To transmit the UL signal from RAU1 toward the CU, the unmodulated Y -pol of λ_1 is used. As shown in Fig. 2, a 25 GHz DPSK signal having a data rate of 128 Mb/s is used to modulate the intensity of λ_1 using a single drive MZM. It may be observed from Eq. (5) that transmitting an optical signal modulated by a high-frequency RF signal over fiber results in frequency-dependent power fading.

The effect of power fading may be eliminated by using single-sideband modulation (Schmuck, 1995). The intensity modulation of Y -pol of λ_1 by the 25 GHz RF signal results in double sideband generation. To eliminate the effect of power fading in our proposed architecture, we transmit the lower sideband of the modulated signal. Therefore, an optical bandpass filter (OBPF) centered at the frequency of $\lambda_0 = \lambda_1 - 25$ GHz and having a bandwidth of 20 GHz is placed at the output of the MZM (Fig. 2). The modulated optical signal at the frequency of λ_0 is wavelength division multiplexed with the remaining optical signals λ_2 , λ_3 , λ_4 , and λ_5 using an OC. The resulting WDM signal is amplified using an EDFA and transmitted toward RAU2 through a 2-km SMF.

The architectures of RAU2, RAU3, and RAU4 are similar to that of RAU1. The UL RF signals from RAU2, RAU3, and RAU4 are transmitted using the single sidebands centered at frequencies λ_1 , λ_2 , and λ_3 , respectively. The unmodulated optical signal at λ_5 is required only for heterodyne detection at RAU4. Therefore, the WDM signal at the output of RAU4 is composed of signals at frequencies of λ_0 , λ_1 , λ_2 , and λ_3 (Fig. 2). It may be observed from Fig. 2 that the RAUs have a simple and cost-effective architecture, where passive optical components are required to perform minimum processing.

The mobile station (MS) is connected to the RF output of each RAU and performs down-conversion and BER measurement on the received RF signal. The input RF signal to the MS is bandpass filtered and amplified using an electronic amplifier (EA). The output of the EA is down-converted using self-mixing by employing a splitter and a mixer (Gulistan and Ghafoor, 2015). The down-converted signal is low-pass filtered and given as input to the BER estimator.

The setup used for performing BER measurements on the UL signals received at the CU is similar to the one used at MSs. As mentioned earlier, after modulating the optical carriers with UL data at the RAUs, single sidebands were filtered out for transmission toward the CU. Single-sideband transmission strongly reduces the effect of frequency-dependent power fading. The single sidebands received at the CU are each coupled with an optical signal that has the same polarization state (Fig. 2). Therefore, a carrier having a frequency difference of 25 GHz with the received optical signal is added.

The addition of a carrier is required to perform heterodyning at the CU. When the signal is composed of single sideband and the carrier is photodetected, a mm-wave signal at a frequency of 25 GHz is generated at the output of the photodetector. BER measurements are performed on the mm-wave signals using self-mixing and low-pass filtering.

3 System performance

In this section we discuss the BER performance of our proposed architecture. The BER measurements are performed at each RAU and at the CU by varying the power of the received optical signal with an optical attenuator and a 3-dB power splitter. One of the outputs of the splitter goes to a power meter, while the other is given as input to the photodetector. Therefore, the power received by the photodetector is the same as recorded by the power meter. Figs. 5a and 5b show the BER versus received power plots for DL and UL signals, respectively.

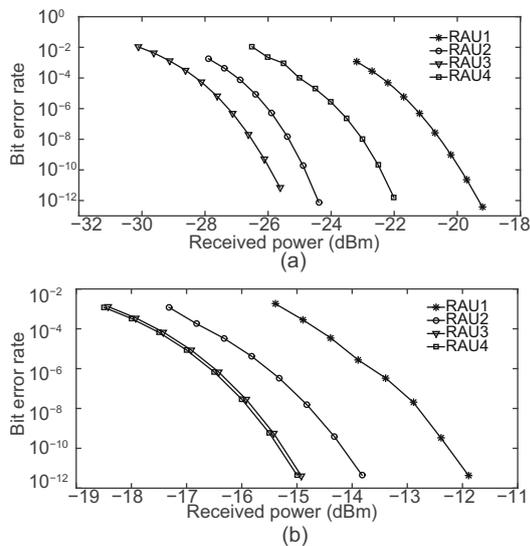


Fig. 5 BER vs. received optical power: (a) DL signals received at RAUs; (b) UL signals received at CU (BER: bit error rate; DL: downlink; RAU: radio access unit; UL: uplink; CU: central unit)

It may be observed from Fig. 5a that the receiver sensitivity for RAU3 is the lowest. This can be explained with the help of the spectral plot of Fig. 3b, where it can be seen that the signal λ_3 , which is used to transmit DL data to RAU3, has the highest OSSR value. It may also be observed from the spectral plot that the OSSR of λ_2 used to transmit DL data to

RAU2 is lower than the OSSR of λ_3 . Therefore, the BER of RAU2 is higher than the BER of RAU3. The OSSR of λ_4 used to transmit DL data to RAU4 is the same as the OSSR of λ_2 used to transmit DL data to RAU2. However, the BER of RAU4 is higher than the BER of RAU2. This is due to the fact that RAU4 is located at a longer distance compared to RAU2, resulting in higher degradation of the signal due to PMD and nonlinear effects. Finally, the BER of RAU1 is the highest among the DL signals. This high BER value is due to the small value of the OSSR of signal λ_1 , which is used to transmit DL data to RAU1. Fig. 5b shows the BER performance of the UL signals received at the CU. As mentioned earlier, single-sideband modulation is used for the transmission of UL signals towards the CU. Furthermore, an optical carrier is added to each single sideband at the CU for heterodyne detection. It may be observed from Fig. 5b that the BER values of RAU3 and RAU4 are almost identical and better than the BER values of RAU1 and RAU2. The reason for better BER values of RAU4 is the short distance of fiber over which the UL signal from RAU4 is transmitted toward the CU. The UL signal from RAU3 to the CU is transmitted over a longer length of fiber compared to RAU4. However, the better OSSR value of λ_3 compared to λ_4 results in almost identical BER performance of RAU3 and RAU4. Furthermore, the receiver sensitivity of RAU2 is higher than the receiver sensitivities of RAU3 and RAU4. This is due to the longer length of fiber over which the UL signal from RAU2 is transmitted. Finally, due to the low OSSR value of λ_1 and longer length of fiber over which it is transmitted, the receiver sensitivity of RAU1 is the highest among the UL signals.

It may be deduced from the results that the direct modulation of a CW laser provides a suitable coherent multi-wavelength source that can be polarization multiplexed to increase the capacity of an RoF link. To increase the number of RAUs connected in the ring architecture, the number of sidebands shown in Fig. 3a needs to be increased. However, there is a limit to the amplitude of the drive voltage applied to the directly modulated laser. Therefore, the number of sidebands and, hence, the number of RAUs, are limited. Furthermore, the distance between the RAUs is adjusted such that the BER of the signal remains in the acceptable range. It was observed that the major factors limiting the BER performance were

PMD and XPM. Therefore, apart from the distance between the RAUs, the peak power of each optical sideband was also appropriately chosen.

4 Conclusions

A duplex RoF DAS architecture is proposed that employs polarization multiplexing and WDM to transmit data between a CU and four different RAUs. A single laser source is used to generate multiple coherent sidebands, where each sideband is used as a separate optical carrier. DL data is transmitted by modulating one of the polarization states of each optical carrier. The UL data is carried by the polarization state, which is transmitted unmodulated from the CU. Each RAU receives and transmits data at the rate of 128 Mb/s and at a mm-wave frequency of 25 GHz. The proposed architecture is cost-effective because wavelengths are reused to simplify the RAU. The system provides enhanced coverage and capacity while maintaining good BER performance. Distortion effects related to high-frequency RF signal transmission are avoided using heterodyne detection at the RAUs and CU. We demonstrated single polarization and single-sideband transmission for carrying high-frequency RF signals from RAUs to the CU.

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