Simplification of millimeter-wave radio-over-fiber system employing heterodyning of uncorrelated optical carriers and self-homodyning of RF signal at the receiver

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Abstract: A simplified millimeter-wave (mm-wave) radio-over-fiber (RoF) system employing a combination of optical heterodyning in signal generation and radio frequency (RF) self-homodyning in data recovery process is proposed and demonstrated. Three variants of the system are considered in which two independent uncorrelated lasers with a frequency offset equal to the desired mm-wave carrier frequency are used to generate the transmitted signal. Uncorrelated phase noise in the resulting mm-wave signal after photodetection was overcome by using RF self-homodyning in the data recovery process. Theoretical analyses followed by experimental results and simulated characterizations confirm the system’s performance. A key advantage of the system is that it avoids the need for high-speed electro-optic and electronic devices operating at the RF carrier frequency at both the central station and base stations.

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References and links


1. Introduction

Applications like high-definition TV (HDTV), video-on-demand (VoD), internet video and peer-to-peer communications will be the dominant component of the total internet traffic in the near future [1]. A large portion of these bandwidth-intensive applications is expected to be supported by current wireless-internet networks [2]. Such expectations can only be met by enabling broadband wireless access (BWA) at speeds no less than 50 to 100 Mbps per user [3]. Existing wireless access schemes, which mainly operate at lower microwave frequencies (<5 GHz), cannot offer such speed due to spectral congestions. Millimeter-wave (mm-wave) frequencies with aggregated channel bandwidths up to 10 GHz are therefore being actively investigated to offer larger transmission bandwidths [4].

Mm-wave radio-over-fiber (RoF) is a key enabler in offering BWA in which base stations (BSs) are connected to the central station (CS) via a fiber feeder network enabling centralized control and monitoring [5,6]. For simplicity, BSs are housed with devices for effective handover only. However, as atmospheric attenuation at mm-wave frequencies can be extremely high, the coverage of each BS is reduced to few 10’s to few 100’s meters [6]. This means that a large number of BSs will be required to provide extensive geographical coverage. Consequently, to make the BWA systems commercially viable, cost-effective and simplified sub-system designs, such as for CSs and BSs, are essential.

Various approaches for the generation and distribution of mm-wave RoF signals have been proposed and can be categorized into two main groups. In the first group, an optical heterodyne technique is employed where the difference between two optical frequencies mixed in a photodetector (PD) generates the desired mm-wave carrier. Several techniques have been demonstrated to generate phase-correlated optical carriers. These include optical phase locking or injection locking of two laser diodes [6,7], frequency-locked lasers [8,9], sub-harmonically-locked lasers [10] and so on. Multimode lasers, in which the modes are not phase locked but are related in frequency, have also been proposed as sources for microwave systems [11,12].

The second approach employs coherent spectral lines from a single light source to generate optical double sideband with carrier (ODSB+C), optical single sideband with carrier (OSSB+C) or optical carrier-suppressed double sideband (OCS-DSB) signal. Such an approach requires high-speed opto-electronic and RF devices including modulators, PDs, local oscillators (LOs), mixers and filters [13–15]. As most of the devices are yet to mature, they are still expensive.

In most lasers, the intensity and phase noise mainly occurs at relatively low frequencies (i.e. kHz to MHz), with linewidths well below the bit rate of the data to be transmitted. Consequently, heterodyned lasers do not necessarily need to be correlated in phase or frequency to be used in mm-wave RoF systems [16–18]. RoF systems employing such uncorrelated lasers can overcome the relevant phase-noise effects by applying incoherent demodulation, such as RF self-homodyning.

We recently proposed and demonstrated such a system [19,20] generating amplitude-shift-key (ASK) modulated mm-wave signal using two uncorrelated, off-the-shelf, distributed feedback (DFB) lasers; from which data was recovered using phase-insensitive RF self-homodyning. This paper extends the previous work by incorporating theoretical analyses and by demonstrating the proposed concept for an additional system configuration. In also includes comparison of results for different configurations through experiments, simulations and numerical analyses.

The new system configuration has the added advantage of reusing the same light-source for both up and downlinks [13]. Moreover, the extension includes analysis and impact of laser noise properties, such as, linewidth and relative intensity noise (RIN) on the recovery of data using RF self-homodyning.
Fig. 1. (a) Millimeter-wave generation schemes exploiting heterodyning of uncorrelated optical carriers, where (a): data is imposed on two independent optical carriers located at CS and separated by 35.75 GHz, similar to an OCS-DSB modulation format (Scheme A), (b): data is imposed on one optical carrier separated by 35.75 GHz from a second independent optical carrier both located at CS, similar to an OSSB + C modulation format (Scheme B), (c): data is imposed on one optical carrier located at CS and coupled with an optical LO (separated by 35.75 GHz) at the BS to enable local optical heterodyning prior to photodetection (Scheme C); (d): describes RF self-homodyning for phase-insensitive recovery of data at the receiver irrespective of heterodyning schemes.

The paper is organized as follows: Section 2 describes the system configurations and theoretical analyses of three heterodyning schemes noted as Scheme A, Scheme B and Scheme C including phase noise generation and signal to noise ratio (SNR) calculations. Section 3 presents the experimental results for each of the schemes. Section 4 characterizes the proposed schemes by simulation and quantifies the effects of variations in laser linewidths and RIN. It also includes a comparison of the performance of RF self-homodyning over a conventional mixer and LO based receiver for the recovery of data. Finally, Section 5 presents the summary of this study.

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2. System configurations and theory of operation

Figures 1(a) to 1(c) presents three transmitter configurations of the proposed RoF system in various generation schemes named as Scheme A, B and C showing the spectra of respective optical mm-wave signal in insets. Figure 1(d) presents RF self-homodyning scheme for phase-insensitive recovery of data at the receiver. The electric fields of the lasers in our system can be represented by:
\[ E_1 \exp \left( j(2\pi f_1 t + \phi_1) \right) \]  
\[ E_2 \exp \left( j(2\pi f_2 t + \phi_2) \right) \]  

Here, \( E_1 \) and \( E_2 \) are the peak amplitudes of the electric fields, \( f_1 \) and \( f_2 \) are the optical frequencies of two lasers such that \( (f_1 - f_2) \) is the desired mm-wave frequency and \( \phi_1 \) and \( \phi_2 \) are the phase variations of each of the two independent lasers. For simplicity in our analysis, we assume \( E_1 = E_2 = 1 \). The modulating signal is sinusoidal and is represented as \( m \cos 2\pi f_m t \); where \( m \) is the modulation index of the single-drive Mach-Zehnder modulator (MZM) and \( m = \left( \frac{V_m}{V_\pi} \right) \). \( V_m \) and \( V_\pi \) represent drive-voltage and the half-wave voltage of the modulator respectively and \( f_m \) is the frequency of the modulating mm-wave signal.

### 2.1 Scheme A

Scheme A presents a transmitter configuration where both of the optical carriers are modulated, as shown in inset of Fig. 1(a). The modulated optical carriers after Taylor series expansion, can be expressed as follows:

\[
A_1(t) = \exp \left( j(2\pi f_1 t + \phi_1) \right) \left[ 1 + jm \cos(2\pi f_m t) \right]
\]

\[
A_2(t) = \exp \left( j(2\pi f_2 t + \phi_2) \right) \left[ 1 + jm \cos(2\pi f_m t) \right]
\]

These expressions of the modulated optical carriers will change after transmission over single-mode fiber (SMF) and can be rewritten as:

\[
A_{1\prime}(t) = \left[ \exp \left( j(2\pi f_1 t + \phi_1 + \phi_0) + \frac{m}{2} \exp \left( j\left(2\pi \left(f_1 + f_m\right) t + \phi_1 + \phi_0\right)\right) + \frac{m}{2} \exp \left( j\left(2\pi \left(f_1 - f_m\right) t + \phi_1 + \phi_0\right)\right) \right] \right. 
\]

\[
A_{2\prime}(t) = \left[ \exp \left( j(2\pi f_2 t + \phi_2 + \phi_0') + \frac{m}{2} \exp \left( j\left(2\pi \left(f_2 + f_m\right) t + \phi_2 + \phi_0'\right)\right) + \frac{m}{2} \exp \left( j\left(2\pi \left(f_2 - f_m\right) t + \phi_2 + \phi_0'\right)\right) \right] \right. 
\]

where, \( \phi_0, \phi_1, \phi_2 \) and \( \phi_0', \phi_1', \phi_2' \) represent the phase delays of the spectral components while propagating through the SMF. The complex conjugates of Eqs. (5) and (6) are:
We assume that both of the modulated optical signals are collinearly polarized. Therefore, after remote heterodyning at the PD, the resulted RF signal can be expressed as:

\[
A'_{i2}(t) = \exp\{j\left(2\pi f_{i2}t + \phi_2 + \phi'_1\right)\} + \frac{m}{2} \exp\{-j\left(2\pi \left(f_2 - f_{i2}\right)t + \phi_2 + \phi'_1\right)\}
\]

(7)

\[
A'_{i2}(t) = \exp\{j\left(2\pi f_{i2}t + \phi_2 + \phi'_1\right)\} + \frac{m}{2} \exp\{-j\left(2\pi \left(f_2 - f_{i2}\right)t + \phi_2 + \phi'_1\right)\}
\]

(8)

Due to the heterodyning detection process, the last nine terms in Eq. (9) clearly show the desired mm-wave frequency at \((f_1 - f_2)\) together with its first and second-order sidebands and the uncorrelated phase \((\phi_1 - \phi_2)\) noise, which can be easily separated by using a suitable bandpass filter. Therefore, after the bandpass filtering, Eq. (9) can be written as,

\[
\begin{align*}
&= \Re \times \left\{ \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi_2) + (\phi_1 - \phi'_2)\right] + \frac{m'^2}{4} \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi'_2)\right] + \frac{m}{4} \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi'_2)\right] \right. \\
&\quad + \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi_2) + (\phi_1 - \phi'_2)\right] + \frac{m'^2}{4} \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi'_2)\right] + \frac{m}{4} \cos\left[2\pi(f_1 - f_{i2})t + (\phi_1 - \phi'_2)\right] \bigg\}
\end{align*}
\]

(9)

where \(\Re\) is the responsivity of the PD.

For simplicity, if we assume that the PD’s responsivity \(\Re = 1\), and fiber dispersion is negligible (i.e. \(\approx 0\)), Eq. (10) can now be written as,
Now, the modulation index values can be generalized as $M$ where, $M$ will vary for $0 \leq m \leq 1$. Hence, Eq. (11) can be simplified as follows:

$$M \cos \left[ 2\pi \left( f_1 - f_2 + n f_m \right) t + (\phi_1 - \phi_2) \right]$$

(Eq. 12)

Here, $n$ is the order of sidebands generated within the range of $-2$ to $+2$ in Eq. (11). Now, in order to apply RF self-homodyning in data recovery process, Eq. (12) is required to be multiplied by itself. To enable such multiplication, let us assume the multiplying terms as:

$$\cos C = M \cos \left[ 2\pi \left( f_1 - f_2 + A f_m \right) t + (\phi_1 - \phi_2) \right]$$

$$\cos D = M \cos \left[ 2\pi \left( f_1 - f_2 + B f_m \right) t + (\phi_1 - \phi_2) \right],$$

where $A$ and $B$ are the respective $n$ values in the range of $-2$ to $+2$ for both $\cos C$ and $\cos D$. After multiplication we get,

$$\cos C \times \cos D$$

$$= \frac{M}{2} \left\{ \cos \left[ 2\pi (A - B) f_m t \right] + \cos \left[ 2\pi \left( 2\left( f_1 - f_2 \right) + \left( A + B \right) f_m \right) t + 2\left( \phi_1 - \phi_2 \right) \right] \right\}$$

(Eq. 13)

Now, let us assume, $A = 1$ for $\cos C$ and $B = 0$ for $\cos D$ and $M = 1$. Therefore, Eq. (13) can be written as,

$$0.5 \left\{ \cos \left( 2\pi f_m t \right) + \cos \left[ 2\pi \left( 2\left( f_1 - f_2 \right) + f_m \right) t + 2\left( \phi_1 - \phi_2 \right) \right] \right\}$$

(Eq. 14)

The first term in Eq. (14) shows the baseband data generated through the RF self-homodyning, which can be recovered by using a suitable low-pass filter (LPF) [20–23].

2.2 Scheme B

Scheme B presents a transmitter configuration where, instead of modulating both of the optical carriers, only one carrier is modulated and the remaining carrier is transmitted as an optical LO alongside the modulated carrier, as shown in inset of Fig. 1(b). Hence, for scheme B, the electric fields of the modulated and the unmodulated optical carriers can be expressed as follows:

$$A_1(t) = \exp \left[ j(2\pi f_1 t + \phi_1) + \frac{m}{2} \exp \left[ j(2\pi f_1 t + \phi_1 + 2\pi f_m t) + \exp \left[j(2\pi f_1 t + \phi_1 - 2\pi f_m t)\right]\right]\right]$$

(Eq. 15)

$$A_2(t) = \exp \left[ 2\pi f_2 t + \phi_2 \right]$$

(Eq. 16)

After transmission over the SMF, Eqs. (5) and (6) can be rewritten as
Similar to Eq. (9), the analytic expression after the PD can be written as

$$A_i(t) = \exp \left[ 2\pi f_i t + \phi_i + \varphi_0 \right]$$

(17)

$$A_e(t) = \exp \left[ 2\pi f_e t + \phi_e + \varphi'_0 \right]$$

(18)

The last three terms in Eq. (19) clearly show the desired modulated mm-wave frequency at $(f_1 - f_2)$ together with the relevant uncorrelated phase $(\phi_1 - \phi_2)$ noise, as explained earlier. As before, phase-insensitive baseband data can be recovered by repeating steps in Eqs. (10)–(14).

2.3 Scheme C

Similar to Scheme B, Scheme C is also comprised of one modulated and one unmodulated optical carrier. The unmodulated carrier, instead of being sent from the CS, is added at the BS before photodetection, as shown in inset of Fig. 1(c). Therefore, in Scheme C, the unmodulated optical carrier is free from any fiber impairments, such as dispersion. This modifies Eq. (18) as,

$$A_{i\text{io}}(t) = \exp \left[ 2\pi f_i t + \phi_i \right]$$

(20)

The analytic expression after PD in this case can be written as

$$i_p(t) = \Re \times \begin{bmatrix}
2 + \frac{m^2}{2} + \frac{m}{2} \cos \left\{ 2\pi f_{i\text{io}} t + (\phi_i - \varphi_0) \right\} + \frac{m}{2} \cos \left\{ 2\pi f_{\text{io}} t + (\varphi_0 - \varphi_2) \right\} \\
+ \frac{m^2}{4} \cos \left\{ 2\pi f_{\text{io}} t + (\varphi_0 - \varphi_2) \right\} \\
+ \cos \left\{ 2\pi \left( f_1 - f_2 \right) t + (\phi_1 - \phi_2) + (\varphi_0) \right\} \\
+ \frac{m}{2} \cos \left\{ 2\pi \left[ (f_1 - f_2) - f_{\text{io}} \right] t + (\phi_1 - \phi_2) + (\varphi_2) \right\} \\
+ \frac{m}{2} \cos \left\{ 2\pi \left[ (f_1 - f_2) + f_{\text{io}} \right] t + (\phi_1 - \phi_2) + (\varphi_2) \right\}
\end{bmatrix}$$

(21)

The rest of the baseband recovery process will remain similar as explained in Eqs. (10)–(14).

2.4 Phase noise due to unlocked heterodyning

Equations (9), (19) and (21) in Sections 2.1-2.3 clearly show the presence of uncorrelated phase noise in the generated mm-wave signals, the effects of which need to be further explored and quantified. In order to do this, for simplicity, let us assume that the generated
mm-wave intermediate frequency (IF) signal is unmodulated. Therefore, generated output after the PD can be simplified as follows:

\[ i_p(t) = \Re \left( P_1 + P_2 \right) + 2\Re \sqrt{P_1 P_2} \cos \left( 2\pi f_{IF} t + \phi_{IF} \right) \]  

(22)

where, \( P_1 \) and \( P_2 \) represent the optical power and \( E_1 = \sqrt{2P_1} \), \( E_2 = \sqrt{2P_2} \), \( f_{IF} = (f_1 - f_2) \) and \( \phi_{IF} = (\phi_1 - \phi_2) \). The power spectral density (PSD) of Eq. (22) can then be written as,

\[ S_S(f) = \Re \left( 1 + \frac{1}{\pi \Delta \nu_{IF}} \frac{2(f-f_{IF})}{\Delta \nu_{IF}} \right)^2 \]  

(23)

where, \( \Delta \nu_{IF} \) is the total full width half-maximum (FWHM) linewidth at the mm-wave IF and \( \Delta \nu_{IF} = \Delta \nu_1 + \Delta \nu_2 \). Here, \( \Delta \nu_1 \) and \( \Delta \nu_2 \) are the linewidths of the unlocked DFB lasers, as explained before. We also assume that the PSD shown in Eq. (22) is Lorentzian laser lineshape.

Now, the RF power of the generated IF signal can be expressed as

\[ P_{IF} = \langle I_p^2(t) \rangle R_L = \frac{1}{2} \left( 2\Re \sqrt{P_1 P_2} \right)^2 R_L \]  

(24)

where, \( \langle \rangle \) denotes the average and \( R_L \) is the terminal impedance at the PD output.

Now, the ratio of the Eqs. (23) and (24) is the single side-band (SSB) phase noise in dBc/Hz, which also can be termed as inverse carrier to noise ratio (CNR) [24]. Therefore, Eqs. (23) and (24) are used to plot the SSB phase noise of the generated mm-wave IF signal at offset frequencies up to 100 MHz, where \( \Delta \nu_{IF} \) is 5.2 MHz, as shown in Fig. 2. Due to higher linewidth contributions (5.2 MHz), SSB phase-noise is calculated to be approximately −72 dBc/Hz at 1 kHz offset. The plot used experimental specifications (described later) of the DFB lasers and the PD for a better clarity, as summarized in Table 1.

**Table 1. Specifications used for the SSB plot**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Linewidth, ( \Delta \nu_{IF} )</td>
<td>(5MHz + 200 KHz) = 5.2 MHz</td>
</tr>
<tr>
<td>Responsivity, ( \Re )</td>
<td>0.6 A/W</td>
</tr>
<tr>
<td>Terminal impedance, ( R_L )</td>
<td>50 Ohm</td>
</tr>
</tbody>
</table>

Fig. 2. SSB phase noise at mm-wave IF due to uncorrelated lasers.
2.5 SNR due to unlocked heterodyning

In order to understand the significance of such unlocked systems on the overall SNR performance, Eq. (24) can be simplified as follows:

\[ P_{IF} = \frac{1}{2} \left( 2\Re \sqrt{P_1 P_2} \right)^2 R_L = \frac{1}{2} I_{av} R_L \]  \hspace{1cm} (25)

Here, \( I_{av} = 2\Re P_1 \) is the average photo-current and is found to be 5.5 mA (\( R_L = 50 \) Ohm) in this case.

Now, the noise PSD of the proposed link consists of noise sources such as, thermal noise, the shot noise, RIN, amplified spontaneous emission (ASE) noise from the erbium doped fiber amplifier (EDFA) and the converted laser phase to intensity noise. The noise from EDFA is regarded as the additional RIN to the system [25].  Same is true for the converted phase to intensity noise [26]. Therefore, the total noise PSD after the PD can be expressed as [27],

\[ P_n = p_{th} + \frac{1}{4} \left( p_{shot} + p_{RIN_{total}} \right) \]  \hspace{1cm} (26)

Here, \( p_{th} = KT \) is the PSD of the thermal noise; \( K \) is the Boltzmann constant and \( T \) is the temperature in Kelvin. \( p_{shot} = 2qI_{av} R_L \) is the PSD of the shot noise where, \( q \) is the electron charge. Finally, \( p_{RIN_{total}} = \left( RIN_{Lasers} + RIN_{ASE} + RIN_{phase} \right)^2 I_{av} R_L \) is the PSD of the total RIN of the system, where, \( RIN_{Lasers} \) is the RIN from lasers, \( RIN_{ASE} \) is the RIN due to ASE noise of EDFA and \( RIN_{phase} \) is the phase to intensity converted noise. Hence, the total noise PSD is

\[ P_n = B_n \left[ p_{th} + \frac{1}{4} \left( p_{shot} + p_{RIN_{total}} \right) \right] \]  \hspace{1cm} (27)

Here, \( B_n \) is the noise bandwidth. Now, assuming that, after the PD, the system goes through a set of low-noise amplifier (LNA) and medium power amplifier (MPA), cascaded noise figure of amplifiers according to Friis formula becomes,

\[ NF_{amp} = NF_{LNA} + \left( \frac{NF_{MPA}}{G_{LNA}} - 1 \right) \]  \hspace{1cm} (28)

Here, \( NF_{amp} \) is the total noise figure of the amplifiers, \( NF_{LNA} \) is the noise figure of the LNA, \( NF_{MPA} \) is the noise figure of the MPA and \( G_{LNA} \) is the gain of the LNA.

Now, considering a directional antenna at 35.75 GHz mm-wave frequencies with transmitting antenna gain of \( G_T = 15 \) dB and receiving antenna gain of \( G_R = 20 \) dB, Friis free-space path loss formula for the line-of-sight link used in our calculation can be expressed in dB as

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal noise after PD</td>
<td>1.6218 \times 10^{-9} \text{ watt}</td>
</tr>
<tr>
<td>Shot noise after PD</td>
<td>0.88 \times 10^{-9} \text{ watt}</td>
</tr>
<tr>
<td>Total RIN after PD</td>
<td>0.4783 \times 10^{-7} \text{ watt}</td>
</tr>
<tr>
<td>Total gain of amplifiers</td>
<td>37 dB</td>
</tr>
<tr>
<td>Noise figure of the amplifiers</td>
<td>2.4 dB</td>
</tr>
<tr>
<td>Path loss for 10 m wireless link</td>
<td>83 dB</td>
</tr>
<tr>
<td>Implementation loss</td>
<td>6 dB</td>
</tr>
<tr>
<td>Thermal noise at the receiver</td>
<td>5.5 \times 10^{-11} \text{ watt}</td>
</tr>
</tbody>
</table>
Here, $PL$ is the path loss due to free space, $d$ is the wireless link distance, $f_{\text{RF}}$ is the mm-wave RF carrier frequency and finally, $c$ is the speed of light in vacuum.

Therefore, the SNR equation for the system using Eqs. (25)–(29) becomes,

$$SNR = \frac{1}{2} \frac{I_0^2 R_L G_{\text{LNA}} G_{\text{MPA}} G_{TX} G_{RX}}{P_{N,M} NF_{\text{amp}} \cdot PL IL KTB NF_{\text{Rx}}}$$

(30)

Here, $G_{\text{MPA}}$ is the gain of the MPA, $IL$ is the implementation loss of the antenna, $KTB_{\text{Rx}}$ is the thermal noise at the RF receiver and $NF_{\text{Rx}}$ is the noise figure at the receiver antenna.

Using the parameters as shown in Table 2, the SNR of the system is calculated to be 29 dB for a wireless link distance of 10 meters for an indoor environment. Multipath-effects were not considered for this calculation as at mm-wave frequencies, multipath scenarios do not affect the SNR performance of the system much as far as the directional antennas are concerned [28]. However, due to the phase noise effects generated after the PD due to unlocked lasers, there will be SNR degradations which can be expressed as $SNR_{\text{unlocked lasers}} = -10 \log(\sigma_p^2)$, where, $\sigma_p$ is the phase noise in rms radian/s due to unlocked lasers and is calculated as 0.628 rms radian/s from the CNR calculations as detailed in section 2.4. SNR degradation is calculated as 4.04 dB in this case and hence, the total SNR of the system is approximately 25 dB.

3. Experimental demonstrations

3.1 Scheme A

Figure 3 shows the setup to demonstrate the proposed concept experimentally in Scheme A. Two free running DFB lasers operating at 1549.214 nm and 1549.50 nm are combined with a 3 dB optical coupler (OC) that gives a frequency offset of 35.75 GHz. Polarization controllers (PC) are used for each of the light-sources before combining. Linewidths of the lasers are 5 MHz and 200 KHz respectively. RIN of both the lasers is ≤-145 dBc/Hz. An ASK formatted 155 Mbps data with a Pseudorandom bit sequence (PRBS) pattern of $2^{31}-1$ and an amplitude of $2 V_{p-p}$ is used to drive the low-speed MZM. $V_{\Pi}$ of the MZM was 4.5 volts. The DSB modulated optical signal is then amplified by an EDFA followed by an optical bandpass filter (OBPF) of 2 nm bandwidth to minimize the out-of-band ASE noise. The signal is then transported over 26.2 km SMF to the BS. A U2T high-speed 50 GHz PIN PD with responsivity of 0.6 A/W is used to detect the modulated optical carriers that generates 35.75 GHz mm-wave signal modulated with 155 Mbps data and a replica of the data at baseband. The mm-wave signal is then amplified using Miteq LNA with a noise figure of 2.3 dB and DBS Microwave MPA to provide around + 30 dB amplification. The need for band-pass electrical filter is avoided by amplifying the PD output with band-limited amplifiers working within 26.5 to 40 GHz that automatically suppresses the baseband replica. In order to demonstrate the back-to-back (BTB) wireless transmission performance of the proposed technique, the amplified signal is then divided by an Anritsu V240C 3 dB power divider operating within DC to 65 GHz prior to self-homodyning using a Miteq mixer. An input power of + 15 dBm is launched to the LO port of the mixer. A variable phase shifter working within 26 to 40 GHz is used at the RF port of the mixer to enable phase-matched multiplication. Finally, a LPF of 545 MHz is used to recover the desired baseband data.

The relevant optical and RF spectra recovered from the experiment are shown in the insets (i) to (iv) of Fig. 3. The spectrum of modulated optical carriers after MZM is shown in inset (i).
Insets (ii) and (iii) show the respective RF spectra after PD and after band-limited amplifiers, whilst inset (iv) shows the recovered baseband data after LPF.

Figure 4 shows the bit-error-rate (BER) curves and eye diagrams for both BTB and after transmission over 26.2 km SMF. The error free (at a BER of $10^{-9}$) recovery of data with a receiver sensitivity of $-16.75$ dBm confirms the functionality of the proposed concept experimentally. The incurred 0.2 dB power penalty is negligible and can be attributed to experimental errors.

![Fig. 4. BER and eye diagrams for Scheme A.](image-url)
### 3.2 Scheme B

Figure 5 shows the setup to demonstrate the proposed concept experimentally in Scheme B with self-explanatory insets. Compared to the setup in Scheme A, the MZM is now moved and placed immediately after the DFB laser operating at 1549.50 nm, keeping the rest of the setup unchanged. Therefore, the modulated optical carrier in Scheme B is combined with an unmodulated optical carrier operating at 1549.214 nm, as shown in Fig. 5. The related power levels of the lasers are controlled to manage equal powers after coupling. As the remaining part of the setup is common to both Schemes A and B, the duplication of the description of the setup is therefore excluded.

![Diagram of Scheme B setup](image)

**Fig. 6.** BER and eye diagrams for Scheme B.
Fig. 7. Experimental set up of Scheme C (top); Insets (i)-(v) show optical and RF spectra at different points of the setup in Scheme C.

Insets (i) to (iv) of Fig. 5 show the relevant optical and RF spectra at different points of the setup, as explained earlier with Scheme A. Similar to Fig. 4, Fig. 6 shows the BER curves and eye diagrams for Scheme B for BTB and after transmission over 26.2 km SMF. An error free (at a BER of $10^{-9}$) recovery of data with a receiver sensitivity of $-15.9$ dBm confirms the functionality of the concept in Scheme B. The incurred power penalty is 0.3 dB which can be attributed to experimental errors.

### 3.3 Scheme C

Figure 7 shows the setup to demonstrate the proposed concept experimentally in Scheme C with self-explanatory insets. Compared to the setups in Scheme A or B, one of the light-sources is moved from the CS to BS to couple the unmodulated optical carrier with the modulated optical carrier just before photodetection. Like before, the power levels of the lasers are controlled to manage equal powers after coupling. Insets (i) to (v) of Fig. 7 also show the relevant optical and RF spectra at different points of the setup, as explained earlier in Schemes A and B. Eye-diagrams and BER curves for the recovered data are presented in...
Fig. 8 for the BTB configuration and after transmission over 26.2 km SMF conditions. At the end of the SMF link, error-free data (at a BER of $10^{-9}$) was recovered at a receiver sensitivity of $-15.9$ dBm. Compared to the BTB condition, a negligible 0.3 dB power penalty is observed that again can be attributed to experimental errors.

As shown earlier in Fig. 1, Scheme A described above can be considered as a perfect presentation of OCS-DSB modulation format, whereas, Scheme B and Scheme C both represent OSSB + C modulation format. Both of the modulation formats are spectrally efficient and dispersion tolerant [29,30]. While both Scheme B and Scheme C have the potential to establish wavelength reuse in uplink path as described in [13,14], Scheme C simplifies the system by avoiding the required optical filtering arrangements. ASK modulation in mm-wave generation and distribution is chosen as it is relatively simple to implement and offers better CNR compared to any multilevel modulation formats, such as quadrature amplitude modulation [4,31].

4. Simulations and characterization
In order to characterize the effects of various system parameters, the proposed concept is simulated by using VPI Transmission maker 7.6™, as shown in Fig. 9. Among three heterodyning schemes, the simulation considers only Scheme A for simplicity and expects
minimum or no difference in outcome, if other schemes are considered. The various simulation parameters are chosen in such a way that the simulated results closely follow the experiments. Figure 10 shows simulated as well as experimental BER curves together. They are almost parallel on top of each other. The difference is negligible (less than 0.2 dB) and can be ignored.

Figure 11 shows the power penalties of the system as a function of RIN of the light-sources. It shows that almost no penalty is observed if RINs are increased from −145 to −130 dBc/Hz. The situation however changes significantly if RINs are increased beyond −130 dBc/Hz; a power penalty of 1dB is observed at a RIN of −120 dBc/Hz. Therefore, RIN needs to be monitored while deploying the system practically, although thankfully most of the current commercially available DFB lasers exhibit a typical RIN of ≤−130 dBc/Hz [32].

BER performance of the system for frequency drifts is measured and shown in Fig. 12. It shows that for a drift of +/- 2.5 GHz, the BER plots sit almost on top of each other, and
Fig. 14. Power penalty vs. laser linewidths for both LO-based and self-homodyned data recovery techniques.

Fig. 15. BER curves at various noise variances in a wireless channel.

due to, robust to the change. Similar robustness can be expected even at higher drifts, as RF self-homodyning is simply a self-multiplication process and has little to do with any specific frequency band.

Typically, higher linewidths of light-sources result in increased phase-noise in any optically heterodyned system [32,33]. To quantify this effect for the proposed system, linewidth of one light-source is increased from 200 KHz to 50 MHz, keeping second source unchanged to 5 MHz. Respective changes in BER performance of the system is shown in Fig. 13. Almost no power penalty is observed for such huge variation of linewidths, as opposed to conventional mixer and LO based receivers. This again can be attributed to the phase-insensitiveness of RF self-homodyned data recovery process, as explained in Section 2.

To further comment on the significance of this data recovery mechanism in the proposed system, the performance of RF self-homodyning is compared with conventional mixer and LO based technique such as coherent demodulation [34,35], as shown in Fig. 14. It shows that with a laser linewidth of up to 40 KHz, both of the data recovery mechanisms are able to recover error-free data at a BER of $10^{-9}$. However, this changes significantly with conventional mixer and LO based technique if the linewidths are increased above 40 KHz and corrupts completely with linewidths as little as 50 KHz. Unlike mixer and LO based technique, RF self-homodyning performs consistently against the various linewidths and shows robustness to linewidths as high as 50 MHz, as shown in Fig. 14.

To get a better insight about the performance of the proposed method in wireless environments, we simulated scheme A with additive white Gaussian noise (AWGN) channel at the receiver. Figure 15 shows the BER performance of the system at different level of noise variances from 0 to 0.3. It is found that at a noise variance of 0.3, error free BER at $10^{-9}$ is not achieved due to increased noise power, which dominates the data recovery process. However, the system performs well within a noise variance of 0.2, as shown in Fig. 15.
5. Conclusion

The demonstrated mm-wave RoF system employing optical heterodyning of uncorrelated lasers for signal generation and RF self-homodyning for phase-insensitive data recovery offers a simplified and cost-effective solution for high-speed wireless access networks. Theoretical analyses and experimental demonstrations show the effectiveness of various unlocked heterodyning schemes. Tolerance of the technique against various laser characteristics such as RIN, linewidth and frequency drift was examined by modeling the system in VPI platforms. For clarity, modeling also incorporated a comparison of the technique with traditional LO based recovery process. Such systems avoid complex phase/frequency locking, high-speed modulators, LO’s and mixing circuitry in the CS and BS of mm-wave RoF systems, potentially enabling Gigabit wireless access at competitive prices.

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