Analysis of mach zehnder modulator response to fiber dispersion in radio over fiber at 60 GHz for multigigabit wireless transmission

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Radio over fiber (RoF) at 60 GHz band is a promising technology for future wireless multi-gigabit transmission in personal, local and wide area networks. With coherent optical orthogonal frequency division multiplexing (CO-OFDM) technique adopted in RoF, to achieve multigigabit speed of transmission, the fiber dispersive effect on the modulated output of Mach Zehnder modulator (MZM) of the RoF system play a critical role in limiting the performance of the system. This paper briefly reviews the multi-gigabit wireless transmission at 60 GHz that indicates the need for radio over fiber architecture, followed by the analysis of MZM response in a dispersive fiber it leads to the power degradation of the transmitted signal over distance. The results for varied bias voltages (i.e., for large and small chirp) at finite extinction ratio indicate that the power degradation due to fiber dispersion at any distance of the fiber can be controlled by appropriate choice of the chirp. Furthermore the results indicate that for a personal and local area networks at 60 GHz, which extends up to few hundred meters the power degradation due to fiber dispersion, can be reduced significantly by varying the chirp without any additional dispersion compensation technique.

Keywords: Radio over fiber, Fiber dispersion, Mach Zehnder modulator, IEEE802.11ad, WiGig, Multigigabit transmission

1 Introduction

In present scenario the whole world is treading towards internet of things; where everyone wants to connect everything, communicate information related to everything, from everywhere, which lead to the increase in the number of interconnected multigigabit transmission speed gadgets inside an office or a house. Also, bandwidth hungry services and applications such as DVB-S2, Ultra HDTV, wireless display and docking and other interactive services that require the transmission of uncompressed videos over wireless networks have driven the wireless networks to evolve to higher band from 2.4 GHz and 5 GHz. The data rate of the future especially, in personal and local area network may reach 10 Gb/s. A huge competition exists across the mm wave standards of high capacity, which are capable of catering the multigigabit transmission needs. The most recent standard 802.11ad of WiGig consortium leads Multi Gigabit wireless standards (MGWS) over the other transmission standards. WiGig recommends the usage of 60 GHz band, the characteristics of which demands the aid of RoF technology for a long distance transmission.

2 Multigabit Wireless Transmission at 60 GHz

The 802.11ad deals with the radio technologies at 60 GHz unlicensed frequency, which is capable of supporting data transmission rate up to 7 Gbps which is 10 times faster than IEEE 802.11n. The channelization of 60 GHz band is typically around 7 GHz, as listed in Table 1.

The band as shown in Fig. 1 extends from 57 GHz to 66 GHz with the middle two channels available

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Low frequency (GHz)</th>
<th>Center frequency (GHz)</th>
<th>High frequency (GHz)</th>
<th>Nyquist bandwidth (MHz)</th>
<th>Roll-off factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>57.240</td>
<td>58.320</td>
<td>59.400</td>
<td>1.728</td>
<td>0.25</td>
</tr>
<tr>
<td>A2</td>
<td>59.400</td>
<td>60.480</td>
<td>61.560</td>
<td>1.728</td>
<td>0.25</td>
</tr>
<tr>
<td>A3</td>
<td>61.560</td>
<td>62.640</td>
<td>63.720</td>
<td>1.728</td>
<td>0.25</td>
</tr>
<tr>
<td>A4</td>
<td>63.720</td>
<td>64.800</td>
<td>65.880</td>
<td>1.728</td>
<td>0.25</td>
</tr>
</tbody>
</table>
around the world. The specification supports 7 Gbps transmission speed with OFDM and 4.6 Gbps over single carrier.

The spectrum even though has an advantage of low multipath impairment; the coverage range is limited due to high channel attenuation as shown in Fig. 2. Beam forming technique is adopted to enable multi-gigabit communication extended up to 10 m distance. But still the spectrum suffers a high penetration loss across the walls as shown in Fig. 3. Thereby the coverage of the spectrum is limited inside a room.

To enhance the coverage of 60 GHz across the rooms of a building or an enterprise a mixed architecture of radio and fiber is adopted widely. The mixed architecture of radio and fiber technology is classified into three broad categories, baseband over fiber, IF over fiber and radio over fiber (RoF). Radio over fiber is widely adopted at 60 GHz, as it enlarges the radio signal coverage and also caters the demand, for immunity to electrical interferences, high linearity, low RF attenuation, high data rates, simple structure RAU and centralized network control and management.

The conceptual representation of the RoF system is shown in Fig. 4. The input RF signal modulates the intensity of the laser light at the head end which is transmitter over fiber to the remote antenna units at any distance from the head end. The optical signal is converted to back RF signal at the remote antenna units enabling the wireless transmission at the site.

The RoF system employs a diverse category of modulation techniques, either direct modulation or external modulators such as Mach Zehnder modulators (MZM). The external modulation is
adopted over the direct modulation due to high speed, high spectral resolution and tunable characteristics. In a MZM the intensity of the light traveling through one or both arms of the Mach Zehnder modulator is modulated by the RF signal which introduces a phase shift exploiting the Pockels effect. The interference of the two waves at the output of the MZM results in the intensity modulation depending on the phase shift induced by the RF signal. In each path the phase modulation is equal with different sign, then the output is purely intensity modulation without any incidental phase modulation or simply the output is chirp free.

The MZM can be directly modulated by the RF signal which leads to the generation of two sidebands. The double side band DSB is affected by chromatic dispersion which leads to phase dispersion and in turn a destructive interference if the phase difference is \( \pi \) at the photo detector. Therefore, a single side band generation is preferred which is generated by a dual drive MZM modulator. Insertion loss, power consumption, nonlinearities and dispersion effects of the dual drive MZM modulator influence the performance of the RoF systems.

3 Analysis of MZM Response in a Dispersive Fiber

The dual drive MZM is widely used modulator for millimeter wave generation in RoF systems. By varying the chirp or the applied drive signals at the arms the optical signal can be transmitted to a longer distance without dispersion compensation. There are several models proposed by researchers for analysis of MZM response in a dispersive fiber. The model proposed by Oliveira et al. is considered for the analysis as the model has shown an comparable results with the other models proposed especially by Devaux et al.

The schematic of the proposed model is shown in Fig. 5. Two novel expression of the optical intensity at the dispersive medium are adopted for the mathematical analysis of MZM RoF system at 60 GHz frequency.

The MZM light wave electric field is given as:

\[
E_{OUT}(t) = \frac{1}{2} \left[ e^{j\Delta \phi_1(t)} + e^{j\Delta \phi_2(t)} \right] e^{j\omega_c t} \quad ... (1)
\]

where \( \omega_c \) is the frequency of the optical carrier, \( \Delta \phi_1(t) \) and \( \Delta \phi_2(t) \) are the change of phase in the arms of MZM due to the applied electric field given as:

\[
\Delta \phi_1(t) = \frac{\pi}{V_n} V_1(t) \quad ... (2)
\]

where \( V_n \) is the half voltage, \( V_1(t) \) is the voltage signals at the arms of MZM and \( \pi/V_n = \eta \) is the index change per volt.

If the modulator is biased at quadrature and if sinusoidal voltages of same frequency \( \omega_m \) of two different peak amplitudes \( V_1 \) and \( V_2 \) are applied at the two arms and the bias voltage \( V_0 \) applied at one of the arm of the MZM, then the phase change at the two arms of the modulator is:

\[
\Delta \phi_1(t) = \eta V_1 \sin(\omega_m t - \frac{\pi}{2})
\]

\[
\Delta \phi_2(t) = \eta V_2 \sin(\omega_m t) \quad ... (3)
\]

Applying Eq. (3) and applying Euler’s formula in Eq. (1), the electrical field of the MZM can be expressed as the sum of Bessel’s function series:

\[
E_{OUT}(t) = \frac{1}{2} \left[ J_0(\eta V_2) - J_0(\eta V_1) \right] e^{j\omega_c t} + \sum_{n=1}^{\infty} \left( J_{2n-1}(\eta V_1) + J_{2n-1}(\eta V_2) \sin(2n-1)\omega_m t \right) \cos(2n\omega_m t) \quad ... (4)
\]

The mathematical analysis can be done using the all four sideband or the first two sidebands. The electrical field output of the MZM with all four side band is expressed as:

\[
E_{OUT+SB}(t) = \left[ E_{DC} + E_{\text{sum}} \sin(\omega_m t) + E_{2\text{sum}} \cos(2\omega_m t) \right] e^{j\omega_c t}
\]

where,

\[
E_{DC} = \frac{1}{2} \left( J_0(\eta V_2) - J_0(\eta V_1) \right)
\]
The parameters $E_{DC}$, $E_{\text{cem}}$ and $E_{\text{clem}}$ is the magnitude of the carrier and the side bands. The RF beat signal at the photo detector is proportional to the optical intensity given as:

$$I_{\text{cem}4SB}(t) = 2|E_{\text{DC}}||E_{\text{cem}}|\cos(\theta_{E_{\text{DC}}} - \theta_{E_{\text{cem}}} + \frac{1}{2}\beta_{2}\omega_{m}^{2}mL)$$  

$$I_{\text{cem}2SB}(t) = 2|E_{\text{DC}}||E_{\text{cem}}|\cos(\theta_{E_{\text{DC}}} - \theta_{E_{\text{cem}}} + \frac{1}{2}\beta_{2}\omega_{m}^{2}mL)$$ ... (6)

where $L$ is the fiber length, $\beta$ is the propagation constant and $\theta_{p}$ is the phase. The optical intensity of the 2SB model is:

$$I_{\text{cem}2SB}(t) = 2|E_{\text{DC}}||E_{\text{cem}}|\cos(\theta_{E_{\text{DC}}} - \theta_{E_{\text{cem}}} + \frac{1}{2}\beta_{2}\omega_{m}^{2}mL)$$  

$4$ Results and Discussion

The numerical analysis of the 4SB and 2SB MZM modulator is performed with the model defined in Eqs. (6) and (7), for the central frequencies of the four channels of IEEE 802.11ad. The half wave voltage $V_{\pi}$ is 5 V, the voltage $V_{1}$ at arm 1 of MZM is 2 V and the voltage $V_{2}$ at arm 2 is -1 and 1.4 V for small chirp and large chirp model, respectively.

The simulation results clearly indicate that the chromatic dispersion effect shifts the phase of the carrier and the sidebands propagating through the fiber. The phase shift introduced depends on the fiber length, RF frequency and the dispersion parameter. This phase shift introduces a phase difference which makes the RF frequency side bands to beat which further results in RF power degradation. Figures 6 and 7 are the 4SB and 2SB model RF power degradation as the function of the fiber length for large chirp model and for the central frequency of the four channels of 60 GHz band. It can be noticed that both the models provide an appreciable results compared to the benchmark paper by Devaux et al.\cite{10}. Figures 9 and 10 show the RF power degradation as the function of fiber length for small chirp in 4SB and 2SB model. Comparing Fig. 6 with Fig. 9 and Fig. 7 with Fig. 10, it is evident that with the change in the bias voltage at the arm the dispersive effect of the fiber can be altered at any distance of the fiber. Thereby the
dispersive effect can be minimized without any additional dispersion compensation. Figures 8 and 11 which illustrate the RF power degradation with frequency at a finite distance of the fiber length, imply that for any defined length of the fiber with appropriate choice of bias voltage and the frequency will further reduce the effect of fiber dispersion. Further the results clearly indicate that the power degradation as a function of chirp pronounces with increase in the RF frequency. Also the power degradation due to the dispersion is insignificant in personal and local area networks which extend few hundred meters and have a great impact on the performance with increase in the length of the fiber.

5 Conclusion

An extensive analysis of channelization and spatial characteristics of 60 GHz is presented in this paper. The analysis of the RoF transmission schemes highlights the significance of MZM based external modulation technique for RoF at 60 GHz. The simulation results indicate that the power degradation of the optical signal due to fiber dispersion varies with distance and chirp or arm voltages of the Mach Zehnder modulator. Also the results indicate that for a personal and local area networks at 60 GHz which extends up to few meters the power degradation due to fiber dispersion can be reduced significantly by varying the chirp or arm voltage of the MZM. Furthermore, either by varying the chirp or with adoption of appropriate fiber dispersion compensation techniques like, usage of dispersion compensated fibers, for the reduction of dispersive effect, the intensity response of the MZM can be transmitted to any distance with low path loss, thereby paving way to the application of 60 GHz signal in a wide area networks for multi-gigabit transmission.

References

2 Wi-Fi Alliance, Wi gig and the future of seamless connectivity, September 2013.